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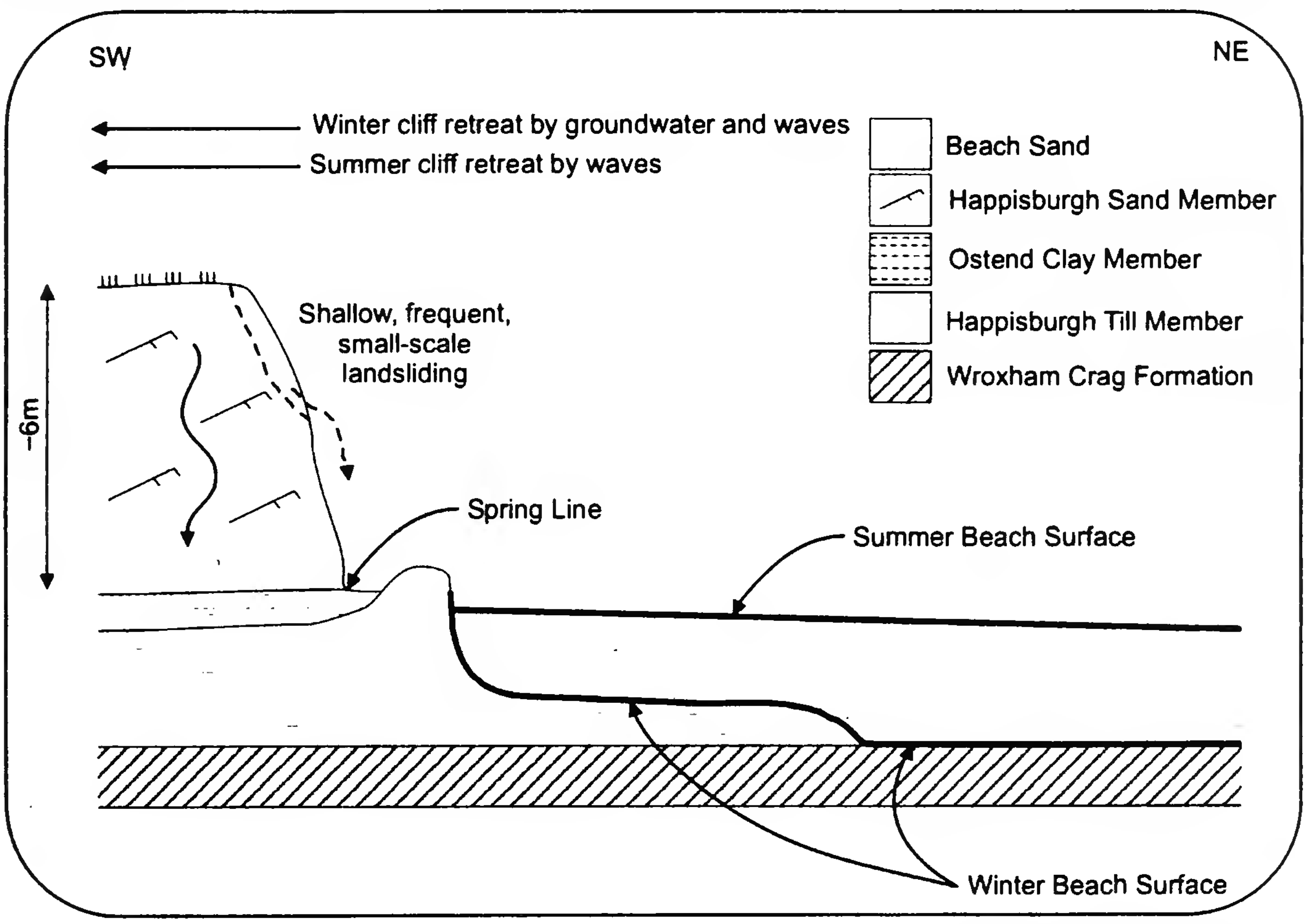

PUBLISHED 2006

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Editor: Julian E. Andrews

School of Environmental Sciences,
University of East Anglia,
Norwich NR4 7TJ

Telephone 01603 592536
FAX 01603 591327
E-mail J.Andrews@uea.ac.uk

EDITORIAL

In recent years the Bulletin has attracted a number of very fine papers that have contributed to better description and interpretation of the geology of Norfolk. The first article by Paul Whittlesea in this Bulletin (56) continues the tradition. With the recent death of Jake Hancock, and with Norman Peake retired from active fieldwork, Paul, with over 30 years of field research experience in Norfolk, can justly claim to be one of the few experts on the local Chalk. In his paper he has collated many years worth of painstaking recording and collection to reconstruct a measured section through the near horizontally-bedded Campanian Chalk between Sheringham and West Runton on the Norfolk coast. Most usefully, he has recorded the section with reference to beach groynes and other geomorphic features such that others can easily locate future finds and fit them into the stratigraphy. Bulletin 56 is not just about Chalk however, there are contributions on Middle Pleistocene sedimentology and stratigraphy, and on new ways to measure coastal cliff retreat. Hopefully something to interest everyone!

I am very grateful to both regular and new contributors for their support in making Bulletin 56 such an interesting issue and already have new contributions in review for Bulletin 57.

INSTRUCTIONS TO AUTHORS

Contributors should submit manuscripts as word-processor hard copy. We accept typewritten copy and consider legible handwritten material for short articles only. When papers are accepted for publication we will request an electronic version. We can handle most word-processing formats although MS Word is preferred.

It is important that the style of the paper, in terms of overall format, capitalisation, punctuation etc. conforms as strictly as possible to that used in Vol. 53 of the Bulletin. Titles and first order headings should be capitalised, centred and in bold print. Second order headings should be centred, bold and lower case. Text should be 1½ line spaced. All measurements should be given in metric units.

References should be arranged alphabetically in the following style.

BALSON, P.S. & CAMERON, T.T.J. 1985. Quaternary mapping offshore East Anglia. *Modern Geology*, **9**, 221-239.

STEERS, J.A. 1960. Physiography and evolution: the physiography and evolution of Scolt Head Island. In: Steers, J.D. (ed.) *Scolt Head Island* (2nd ed.), 12-66, Heffer, Cambridge.

BLACK, R.M. 1988. *The Elements of Palaeontology*. 2nd Ed., Cambridge University Press, Cambridge. 404pp.

Illustrations should be drawn with thin dense black ink lines. Thick lines, close stipple or patches of solid black or grey should be avoided as these can spread in printing. Original illustrations should, before reproduction, be not more than **175mm by 255mm**. Full use should be made of the first (horizontal) dimension which corresponds to the width of print on the page, but the second (vertical) dimension is an upper limit only. Half tone photographic plates are acceptable when their use is warranted by the subject matter, provided the originals exhibit good contrast.

The editors welcome original research papers, notes, comments, discussion, and review articles relevant to the geology of **East Anglia** as a whole, and do not restrict consideration to articles covering Norfolk alone. All papers are independently refereed by at least one reviewer.

THE INTERTIDAL OUTCROP OF THE UPPER CAMPANIAN BEESTON CHALK BETWEEN SHERINGHAM AND WEST RUNTON, NORFOLK

Paul S. Whittlesea

8 Eaton Old Hall, Hurd Road, Eaton

Norwich, Norfolk, NR4 7BE

ABSTRACT

For the first time a detailed description is provided of the intertidal outcrop of the middle and upper Beeston Chalk from Sheringham to West Runton including notes on anomalous features. The outcrop has been logged between modern beach groynes: these define frames that can be located with ease by other workers. The positions of mappable marker horizons are also located: these are chiefly flint bands, hardgrounds, major omission surfaces and beds where peak abundances of belemnites, echinoids and sponges are recognisable either alone or in combination. These recordings together with knowledge of the structure of the Upper Cretaceous in the county, is used to prepare a synthetic vertical section for the Beeston Chalk in this part of the Norfolk coast.

INTRODUCTION

The overall structure of the solid geology of Norfolk has been known since the early 19th century (Woodward, 1833). In essence, the dip is gentle and easterly with a strike approximately due north - south. From boring records Boswell (1916) was able to construct a contour map of the chalk surface and estimate the formational dip of the Chalk in central Norfolk (Boswell, 1920) as 6.6 m/km, noting that it diminished towards the east. Boswell noted that the dip of the chalk surface is somewhat lower at 1.5 m/km, thereby preserving younger zones towards the east. (All measurements published in imperial units have been converted here to their metric equivalent). The formational dip in south Norfolk is about half that in central Norfolk resulting in a broadening of the outcrop there.

The upper Upper Campanian Norwich Chalk (see glossary and Fig. 1) has long been recognised as having a distinctive character. Earlier attempts were focussed on

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correlating units within the county, although workers were not slow to comment when they recognised faunas similar to those from other locations in the UK and on the continent. The work by Brydone (1930, 1938), Peake & Hancock (1961, 1970), and Wood (1988) contributed greatly to knowledge of the "Norwich Chalk" resulting in the recognition of 11 units mainly based on faunal assemblages (Fig. 1; Wood 1988 column). Christensen (1995, pp. 8-9 and fig. 2) divided the Beeston Chalk into 3 further units using belemnite assemblages, bringing the total number of units recognisable to 13 (Fig. 1; Christensen 1995 columns). Work by Johansen & Surlyk (1990) using micromorphic brachiopods and by Christensen (1995) using belemnites confirmed long held expectations that parts of the East Norfolk Chalk (ENC) could be correlated with continental localities and horizons. Johansen & Surlyk (1990), noting the somewhat diffuse criteria employed by earlier workers, attempted to create a robust lithostratigraphic framework. They recognised and named 5 Campanian units (Fig. 1) and 3 Lower Maastrichtian units, each of member rank In practice, the boundaries between these were closely similar to those previously in use in other stratigraphic schemes and in several cases employ current or resurrect old names, (e.g. Eaton Chalk Member). No attempt was made to group these members into one or more formations. Their biostratigraphic scheme produced only two zones for the Upper Campanian (Fig. 1) and three for the Lower Maastrichtian. Christensen (1995) divided the Upper Campanian into seven divisions (Fig. 1) some on the basis of endemic species. Hence the degree of resolution achieved within the county was poorer in each case.

Work by Pitchford (1991) demonstrated that it was possible to correlate the type section of the Weybourne Chalk in the cliff between Weybourne Hope and Sheringham with part of that at the then extant pit at Keswick to the south west of Norwich using flint bands. It is intended that the data reported here will provide a basis for experimenting with correlations between the coastal outcrop (Sheringham to West Runton; Fig. 2) and that inland.

Difficulties associated with mapping the Beeston Chalk Member

The regional dip of the Chalk surface brings it to within a few metres of Ordnance Datum in the study area between Sheringham and West Runton (Fig. 2). East of that point, and certainly at Cromer, the chalk surface is very close to, or at, low tide mark. Exposure of a complete, clean, intertidal coastal section has never been present for a sufficiently long period to enable easily integrated observations to be made. Hence it is necessary to make

Peake & Hancock (1961) "faunal belts"	**Wood (1988)**	**Johansen & Surlyk (1990) Lithostratigraphy**	**Johansson & Surlyk (1990) brachiopod biostratigraphy**	**Christensen (1995) belemnite biostratigraphy**	**Christensen (1995) relationship to Wood (1988)**
Paramoudra Chalk	Paramoudra 2 Chalk	Paramoudra Chalk Member	*longicollis - jasmundi*	*B. minor II & ex. gr. langei-najdini*	Paramoudra 2 Chalk
	Paramoudra 1 Chalk			*Belemnitella minor II*	Paramoudra 1 Chalk
Beeston Chalk	Beeston Chalk	Beeston Chalk Member	*tenuicostata - longicollis*	*B. minor I, pauli & najdini*	Beeston 3 Chalk
				B. minor I & langei	Beeston 2 Chalk
				Belemnitella minor I	Beeston 1 Chalk
Catton Sponge Beds (2)*	Catton Sponge Beds (3)*	Catton Sponge Beds			Catton Sponge Beds (3)*
Weybourne Chalk	Weybourne 3 Chalk	Weybourne Chalk Member		*Belemnitella woodi*	Weybourne Chalk
	Weybourne 2 Chalk				
	Weybourne 1 Chalk				
Eaton Chalk	Pre-Weybourne 5 Chalk	Eaton Chalk Member		*Belemnitella mucronata*	Pre-Weybourne 5 Chalk
	Pre-Weybourne 4 Chalk				Pre-Weybourne 4 Chalk
	Pre-Weybourne 3 Chalk				Pre-Weybourne 3 Chalk
	Pre-Weybourne 2 Chalk			?	?
Basal *mucronata*	Pre-Weybourne 1 Chalk	?		?	?
5 units	**11 units**	**5 members**	**2 'zones'**	**7 zones or zonal assemblages**	

Fig. 1. Stratigraphy of the Norwich Chalk (Campanian).

*The Catton Sponge Beds are a series of major hardgrounds that straddle the junction between the Weybourne and Beeston Chalks. They are not a biostratigraphic unit in their own right although Johansen & Surlyk (1990) accord them member rank in their lithostratigraphy. Peake & Hancock (1961) initially recognised two sponge beds at the stratotype. Wood (1988) subsequently identified a third lower in the sequence there, and Peake & Hancock (2000) reported four at Castle Mall, Norwich, the newest being at the top of the sequence. The terminal erosion surface of the second hardground from the base marks the top of the Weybourne Chalk.

Data in this table is from Peake & Hancock (1961, 1970), Wood (1988), Johansen & Surlyk (1990), Christensen (1995) and Whittlesea (2006). Precise correlation between units cannot be assumed as different criteria are used for litho- and biostratigraphy.

a patchwork of observations and integrate these. Furthermore, the low dip of the Chalk (~1°, 5m/km) often makes it difficult to recognise boundaries between closely spaced marker horizons, principally flint bands, even when they are strongly characterised. Thus it took observations over a period of several years to collect and validate sufficient data to justify producing this paper. Future observations should clarify outstanding problems.

The Beeston Chalk Member has never been well-exposed inland, and no geologist has ever attempted to correlate the many small sections exposing various parts of it, even when they were available during the 19th and early 20th century. There are faunal and lithological changes that enable the provisional recognition of two and possibly three sub-divisions. There is also subtle endemism present amongst the benthos arrayed north - south, of which some is clearly diachronous. This also seems to be true of some of the lithofacies. The latter observations and their interpretation will be discussed in greater detail in a forthcoming paper dealing with the correlation of the coastal and inland exposures.

Methods

The data collected for this project have been used to construct a synthetic vertical section (SVS) for the coastal outcrop of the Beeston Chalk (Fig. 3). Constructing a SVS from a horizontal section, such as a beach, is theoretically simple. It is necessary only to measure base-to-base separations of discrete marker horizons and then using knowledge of the strike, dip and basic trigonometry, calculate the vertical separations of the marker horizons. However, in Norfolk where dips are very low and marker horizons relatively closely spaced or laterally impersistant, it can be very hard to discriminate between, or detect, these.

MARKER HORIZONS AND THEIR CHARACTERS

Flint bands and flints

Because of the potential confusion over the agent(s) responsible for the topology of a flint band, especially where only a horizontal section is available, descriptive terms have generally been preferred to interpretive terms. For example, "labyrinthine" is preferred to "thalassinid" where an outcrop consists of horizontally interconnected sinuously weaving flints and it is not possible to be completely satisfied that it is a burrow system: these may extend as much as 2 m below the sea floor (Bromley and Ekdale, 1984). Hence, ostensibly "labyrinthine" flint bands may actually be just the tops of high (>7 cm),

sinuous ridges on more deeply hidden massive tabulate flints. In several cases that is exactly the case.

"Chain mail" flint bands are here defined as bands of small (typically averaging 40 cm) diameter ring flints united with their neighbours at their outer circumference. They may be interconnected by short struts of flint arising from the outer circumference rather than by actual margin-to-margin contact ("capstan flints"). Ring and capstan flints grade into one another: a ring flint may have margin-to-margin contact on one side and struts connecting it to its neighbour on the other. However horizons tend to be characterised by flints being of overwhelmingly one type.

More generally, flint bands are not bounded by perfect, parallel, Euclidean planes: their upper surface in particular almost always bears ridges and depressions of varying widths and heights the appearance of which will alter dramatically depending on how much chalk has been eroded. Where reference is made to "overgrown thalassinid" flints, in this paper it means that the flint overgrowth was contemporaneous or penecontemporaneous with flint formation.

The following list of attributes was applied to flint bands and individual flints:

Band: [tabulate: perforate/ imperforate, separate flints: closely- / well-spaced], topology [(small to medium sized) ring/ capstan/ labyrinthine/ cow-pat/ paramoudra incorporated/ metamoudra / huge turret flint (incorporated/ associated), /(large to very large) single or multiple concentric ring or capstan], base [smooth horizontal, turreted], top [sinuous ridges, smooth rounded crests, sharp acuminate ridges, turreted].

Flints (individual): topology: [nodular, spindly, ring (used for small to medium sized flints; the flint band that incorporates them often consists of little else), circle (used for occasional large or very large perforate flint rings incorporated into the thickness of a band), capstan, huge turreted at base and top, metamoudra, paramoudra] cortex [thickness: none/thin/thick, smooth/ rough/ perforated by burrows, colour: grey/white, pseudo-sutures: yes/no]; interior: [colour: grey/ mottled/ black, carious: yes/no]; massive turreted: base/top/both/neither.

In the Beeston Chalk Member, unlike the lower Paramoudra-1 Chalk, there are no units characterised by regularly spaced, aligned columns of tall, massive paramoudras. Paramoudras do occur and may be characteristic of a band, but they are usually incorporated into it and of the same general thickness. Of course at some horizons, the

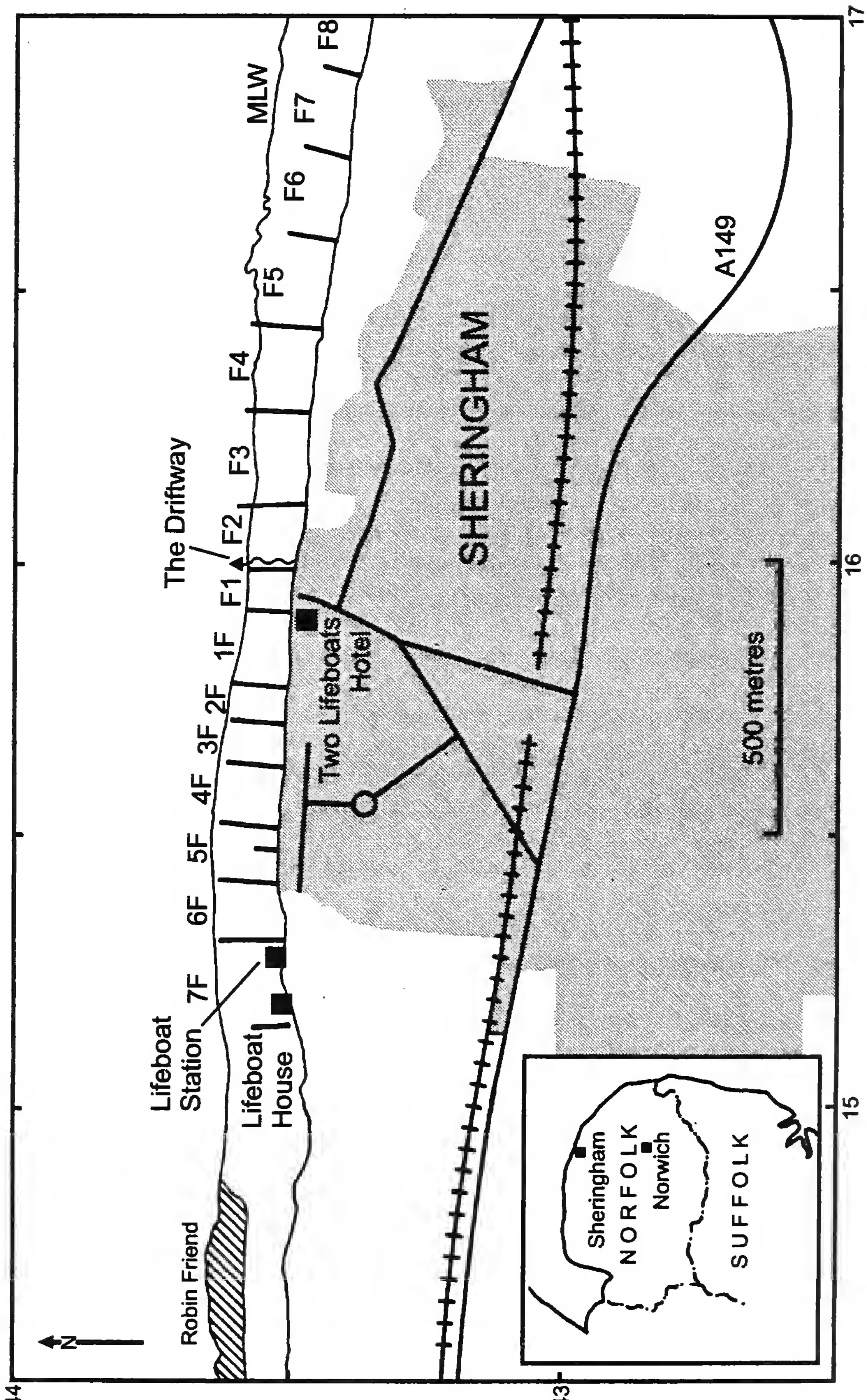

Fig. 2 [see legend p. 9]

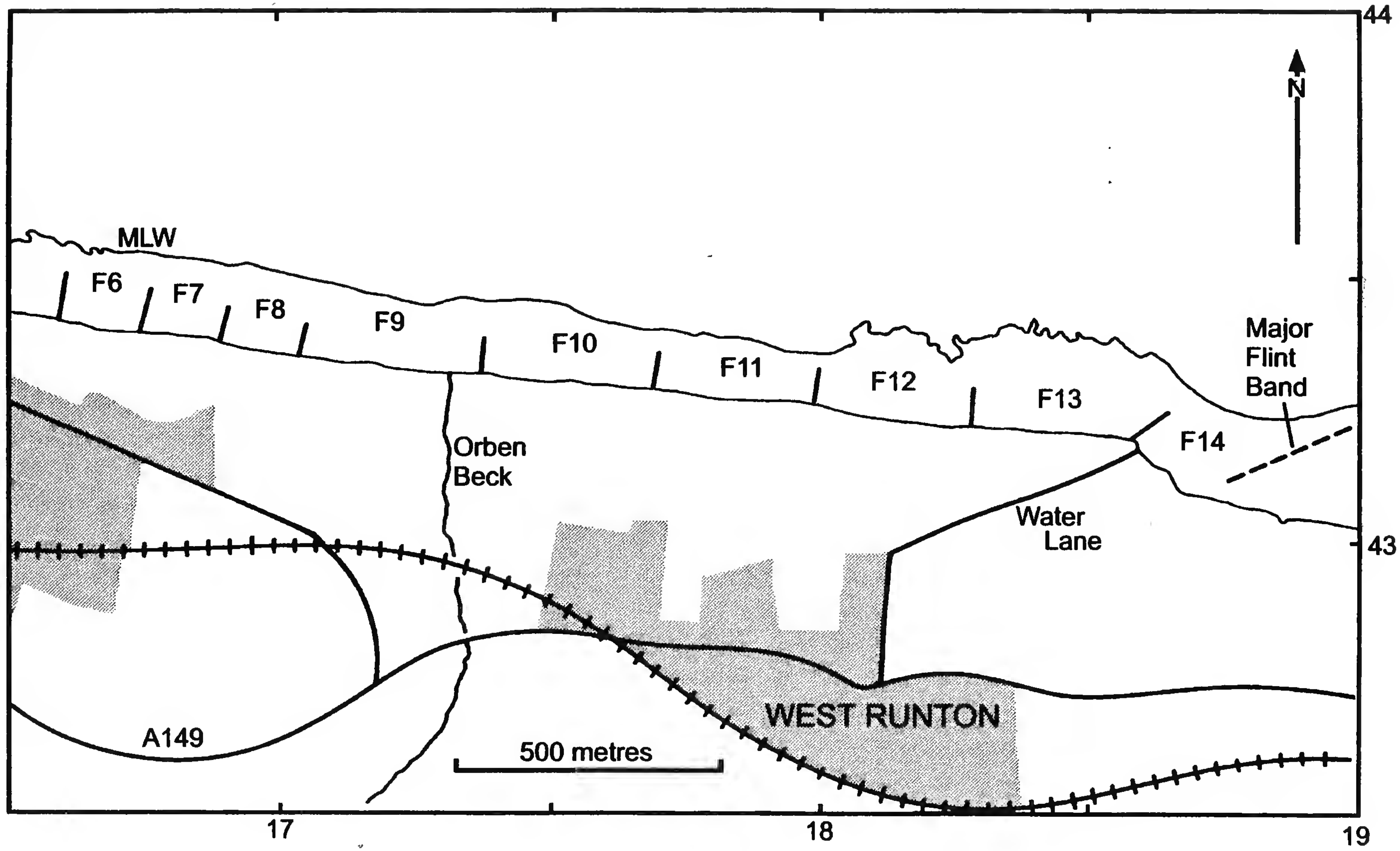

Fig. 2 [continued] Sketch map of the foreshore between Sheringham and West Runton. Frame numbers (F1, F2 etc.) are shown between marker groynes. The easternmost edge of Frame 14 is approximately 100 m east of Water Lane, West Runton. National grid numbers are marked on the map boundary to aid orientation. Robin Friend is an outcrop of one of the higher hardgrounds in the Weybourne 3 Chalk (Fig. 1).

height of isolated huge flints is much greater than the thickness of the flint band they are associated with or integrated into.

Isolated scatterings of small-medium size flints that might with confidence be identified in an inland vertical section as constituting a band were excluded as markers because on the coast these are too easily eroded or confused with the turreted crests of huge isolated flints and some ostensibly tabulate bands that occur at several horizons.

Sharp colour change of chalk (west-east)

At least two horizons show a very sharp colour change from grey to yellow chalk (and vice-versa) and from yellow to white chalk. Grey chalk incorporates abundant finely dispersed iron sulphide (pyrite); yellow chalk incorporates hydrated iron oxides. In white chalks, pyrite may be present as films on joint surfaces, flint and chalk nodules, or occur as discrete crystalline masses. The change from grey or white to yellow chalk is very sharp at two horizons, and is followed by a more gradual reversion usually to white chalk that often contains large nodules of crystalline pyrite. When collected, some of these nodules prove to be meta-stable and disintegrate within a few weeks or months into a white powder; others have remained unchanged for decades. The reason for the varying stability is not understood.

Transitions between chalk facies

Abrupt changes within or between any of the following may provide marker horizons: nodular chalks (sudden change in the average nodule size), a major omission surface (MOS), or a hardground.

Abundant echinoid horizons (AEH's)

These are horizons where echinoids, almost invariably *Echinocorys*, exhibit a clear peak in abundance – usually above a MOS. Echinoids are not necessarily well-preserved, or in life orientation: they usually have a distinctive epifauna.

Abundant belemnite horizons (ABH's)

There are many horizons in the chalk where belemnite guards peak in abundance. Often they are above MOS's or hardgrounds, but not always. In the former instance they are more likely to be sea floor accumulates that were not diluted by sedimentation. In other cases, scouring and winnowing of unconsolidated sediment containing any guards above

an incipient hardground would have produced a remanié deposit including those on the newly revealed hardground. Boring by contemporaneous bacteria, algae, fungi, cirripedes, sponges and other benthic organisms may have affected guards. These in turn may have been predated by grazing organisms, (e.g. regular echinoids, fish) and/or been encrusted by bryozoa, brachiopods and serpulids. Where damage or encrustation is restricted to one surface it demonstrates that the guard had not been rolled on the sea floor. All levels of contemporaneous biodegradation may co-exist from none to intense.

Geographically limited marker features

Some marker features have limited geographical extent and utility; e.g. the colour of individual chalk beds, (finely dispersed pyrite oxidises once above the water table and exposed to the air) is useless inland; any increase in sedimentation rate towards the North Sea basin may be associated with an increase in the number and greater spacing of flint bands or splitting of hardgrounds and other MOS's; the presence of "sparse" flint bands or those consisting only of isolated nodules that have been logged inland may go unrecorded at the coast due to erosion or recognition difficulties.

The Catton Sponge Beds

The Catton Sponge Beds crop out at their stratotype, Campling's Pit, Catton Grove SSSI (NGR TG 229 109). They are a series of up to four evenly spaced hardgrounds separated by 0.5 – 0.75 m, sometimes as much as a metre. They are numbered from the base up. Their first modern formal description was by Peake and Hancock (1961) who recognised two hardgrounds, the lower being very strongly developed. This is the main Catton Sponge Bed, the terminal erosion surface of which marks the upper surface of the Weybourne Chalk Member. Subsequently, Wood (1988) revisited the site and identified a third hardground beneath the main Catton Sponge Bed. When reviewing the excavation for what was to become the Castle Mall in central Norwich, Peake recognised four hardgrounds, (Peake & Hancock, 2000). From the observations made it could not be ascertained whether the presence of only three hardgrounds elsewhere was due to one pincjing-out laterally or merging with one of the others: a feature known to occur in the Lower Maastrichtian Sponge Beds (pers. obs.). Subsequently, Peake (pers. comm.) declared that all four of the Catton Sponge Beds seen at the Castle Mall temporary excavation had been recognised by him on the north Norfolk coast. Palaeontologically, the obvious macrofaunal feature associated with crossing the main Catton Sponge Bed is

a change in the echinoid fauna and a marked increase in abundance of the brachiopod *Carneithyris carnea* (J. Sowerby).

Mapping procedures

The low dip of the Chalk (versus that of the Chalk surface) dictated that the section be mapped from west to east in order to ensure that the base of flint bands were located accurately and that their true nature was determined. The flint bands crop out in a line approximately 30 degrees to the shore-line (trending ~WSW-ENE) hence it is necessary that any base-to-base measurements of the horizontal separation of any pair of flint bands is made at the same height above the sea margin during a logging session, otherwise the figure logged will be exaggerated. However, the considerable breadth of the beach at low tide is jointly attributable to the tidal range (some 2-4 m) and the gentle shelving of the beach. Hence specimens collected along a line perpendicular to the low water mark (LWM) may be separated by 2-4 m, a degree of imprecision that would be unacceptable for research in a quarry or cliff section. Differing heights of adjacent exposures often made it necessary to deviate from this protocol. Some figures are thus provisional.

Location reference frames

The length of coast from the last groyne at the west end of the promenade adjacent to the Lifeboat House (TG 143 436) at Sheringham to the major flint band running out across the beach immediately to the east of Water Lane, West Runton (TG 187 433) is 4.4 km (determined using a 1:10,000 scale map of the coast prepared for sea defence work by Hobbs & English Consulting Engineers). Groynes provided reference points for observations; each pair of groynes enclosing a space referred to as a "Frame" (see Fig. 2). Frame "F1" is at the point (NGR TG 159 435) where Sheringham High Street meets the promenade in front of the Two Lifeboats Hotel. Frames east of here run to F14, although as noted above, a major flint band rather than a groyne defines the easternmost boundary of F14. (The last groyne east of Sheringham defines the easternmost boundary of F13. The next and very low groynes start just to the west of Cromer.) Immediately to the east of F13 is Water Lane, West Runton that provides access to the beach. The lengths of individual "Frames" were also obtained from the map and are given in Table 1. Frames running west from F1 were identified as "1F" ... "6F", (i.e. 1F and F1 are back-to-back), but data from these are not included in this paper (see below).

To add further precision to observations, the width of each individual Frame was divided into tenths. Thus "3F.3" means that the observation was made at a distance three-tenths east of the start of that Frame ('3F.0'). As the orientation of the beds became known the need to include data where a specimen had been collected with reference to the low, median or high water mark was included. Accordingly, location data for specimens was recorded as (e.g.) "F12.3:LWM", "F9.2:MWM" and "F4.7:HWM". Later codes were abbreviated to "F12.3L", "F9.2M" and "F4.7H".

These data were incorporated as the sub-side code given to every specimen in the author's collection where the site is large enough to justify sub-division. Further details of this are included in Appendix A. References to (e.g.) "F3" versus "F3.0" refer to comments applicable to the whole of the Frame.

Geographic scope of detailed survey: F3-F14

The poor exposure at the western end of this stretch of coast, (7F-6F, 4F-F2 & F4 were never exposed, 5F and F3 only occasionally so and then only poorly), restricted the research area to the east side of Sheringham from F3.0 to F15.0 (i.e. the easternmost boundary of F14 defined by the base of the first major flint band immediately to the east of Water Lane at West Runton). The Beeston Chalk Member is followed by the Paramoudra-1 Chalk whose base is characterised by the "Bone Bed", (Peake & Hancock, 1961) immediately to the east of F15.0, (NGR TG 190 432). The third Catton Sponge Bed (CSB) is believed to be in F1 (Mortimore, Wood & Gallois, 2001, p. 358) and is taken to be at F1.0 in order to provide a precise reference datum for the base of the SVS. This designation is important when attempting to correlate the coast with inland sections.

PROBLEMS

The figure used for the formational dip in this paper is 5 m/km. Hence, 100m of beach represents 0.5 m thickness of chalk. An individual flint band might have an average thickness of 0.3 m. Therefore, the band would crop out over a 60 m width of beach before the dip took it out of sight. Hence, a pair of bands 0.3 m thick, spaced less than 0.3 m apart, would have an overlapping or apparently continuous outcrop of up to 120 m. At Caistor St. Edmund (CSE) chalk pit, Wood (1988, fig. 8) recorded five bands of roughly similar thickness in a metre and alluded to their impersistant nature. On the coast it was impossible to identify the bases of these over their 200 m outcrop.

At the outfall of Orben Beck (NGR TG 173 433) there is a channel of diamicton and of reconstituted chalk running across the beach just east of the centre of F9 and some substantial blocks of steeply inclined Stone Bed from the Crag nearby. This has been interpreted as an infilled "gravity collapse structure", (N. B. Peake, pers. comm.), presumably formed when the roof of a subterranean stream, that ran out beneath the modern beach, failed. It is not possible to make any observations of the chalk at this point but the width of beach affected is narrow enough for reasonable inferences about the stratigraphy to be made.

From F12.9 to F13.9 the beach is covered with a continuous layer of flint (25-35 cm thick where it can be measured) of constant character. With an outcrop in excess of 330 m wide the flint band should be ~1.4 m thick; it clearly is not. In addition, the Crag-Chalk surface boundary drops abruptly by ~1.5 m between F13.9 and F14.0; a concrete slipway giving access to the beach from Water Lane obscures the geology at this point. It is possible that at this location there are several, closely spaced flint bands of identical nature having an overlapping outcrop whose individual bases cannot be discerned. A single flint band 30 cm thick would have an outcrop 60 m wide, it would require 5 or 6 to cover 330 m – with virtually no chalk in between them. However, a feature of the flint bands seen along this stretch of coast at LWM is that their bases can be discerned quite easily as curving ribs of flint rubble collected on and above the leading (western) edge of each band as it extends out to sea. There is no evidence here of more than two such features. But there may be a small normal or reverse fault at Water Lane that moved after the Crag was deposited.

Observations

The following account describes the coast section including data on marker horizons, facies and fauna and should be read with reference to Figs. 2 and 3 and Tables 1 and 2. Courtesy of Mr. C. J. Wood, who made available copies of his unpublished field notes of the coast compiled before new sea-defences stabilised the sand cover in the vicinity of Sheringham, it has been possible to extend the section west to F2 and to include and augment data on F2 – F7. Where the author has been unable to make any observations of a horizon those made by Mr. Wood have been employed. (Despite having stated a preference for "descriptive" rather than "interpretative" adjectives, if Mr. Wood used these they have been kept.) Where it has been possible to supplement Mr. Wood's field notes a degree of discretion has been exercised.

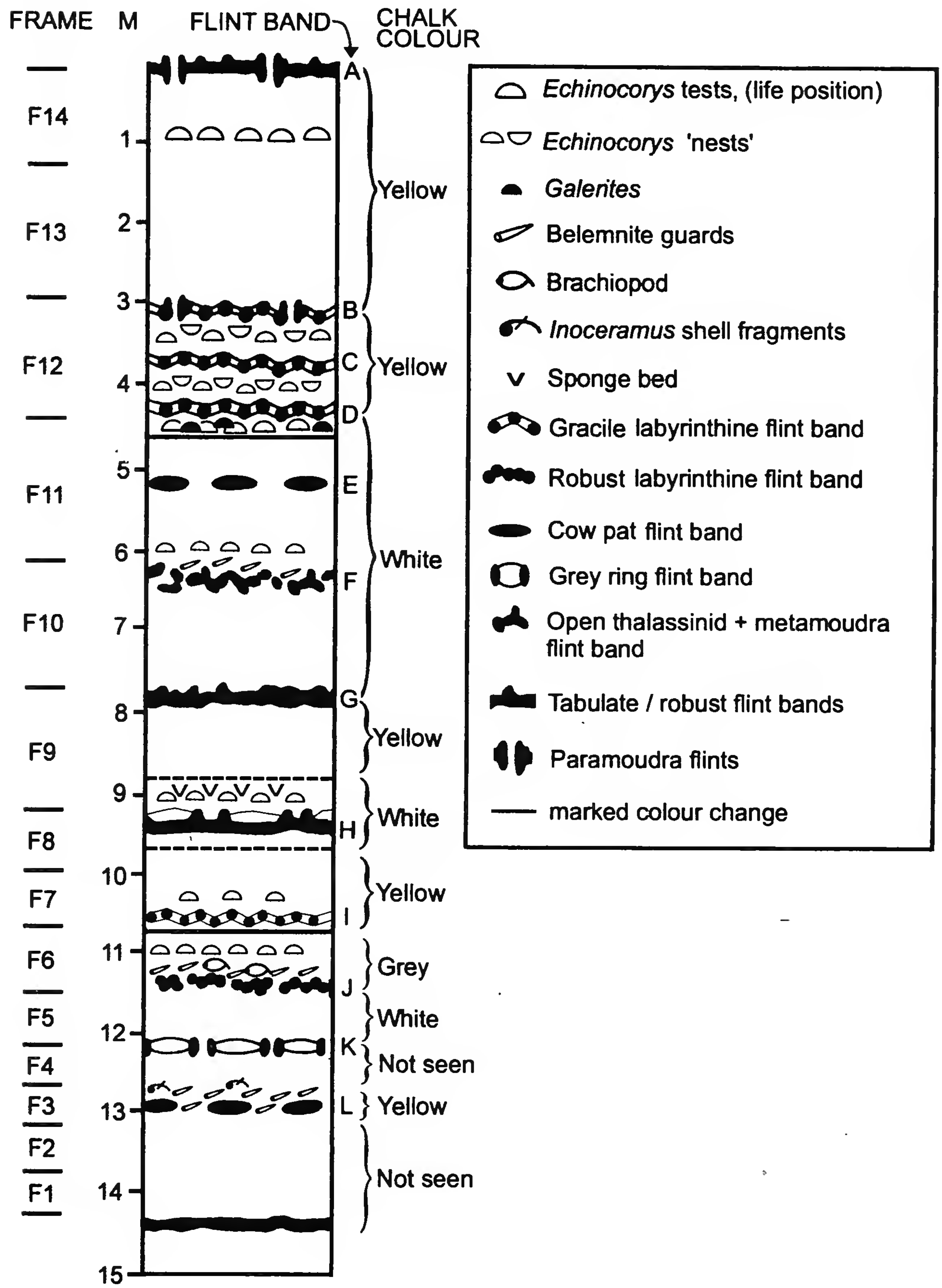

Fig. 3. Synthetic vertical section for the Chalk between "The Driftway" at Sheringham (a storm drain outfall but formerly a stream that excavated a (now largely infilled) channel) to the easternmost edge of F14 approximately 100m east of Water Lane, West Runton. The figure indicates the position of frames, thickness of the section (based on an assumed easterly dip of 5 m/km), frame contents and presence of marker horizons. The text gives detailed information about each horizon.

Table 1. Frame number, horizontal width and calculated chalk thickness/separation (based on an estimated dip of 5 m/km), and an overview of the main Chalk features.

Frame EAST	Width	Thickness/ Separation (m)	MAIN FEATURES
F14	250	1.25	Western-most edge of massive flint band: **TG 187 433**
F13	330	1.65	Anomalously wide flint band in yellow chalk followed at F14.1-F14.9 by the Water Lane MOS of yellow phosphatic chalk incorporating an AEH & ABH.
F12	320	1.60	Old Butts MOSs incorporating 3 x (MOS + AEH), yellow chalk.
F11	321	1.60	Soft white chalk with sparse cowpat flint band.
F10	310	1.55	Nodular white chalk, open *thalassinid, MOS, ABH, AEH.
F9	310	1.55	Orben Beck hardground (top) yellow chalk.
F8	145	0.73	Orben Beck hardground (base) incorporating AEH, white chalk.
F7	145	0.73	Beeston Hill hardground (top) yellow chalk with [flint] ammonites, echinoids, bivalves, belemnites and brachiopods. TG 168 434
F6	155	0.78	Beeston Hill hardground (base) incorporating AEH, hard grey chalk with many belemnites, brachiopods, bivalves and sponges.
F5	124	0.62	Semi-continuous *thalassinid flint with white pyritic chalk.
F4	93	0.47	Grey ring flint with *thalassinid flint and belemnites.
F3	103	0.52	Sparse cowpat flint band in yellow chalk with *Inoceramus*.
F2	113	0.57	Possible thalassinid flint band in yellow chalk.
F1	113	0.57	Not seen, in front of the Two Lifeboats Hotel, but supposedly including the uppermost of the three Catton Sponge Beds known to Mortimore, Wood & Gallois (2001): **TG 159 435**
1F	70	0.35	Not seen.
2F	200	1.00	Very rarely seen, has yielded a tiny colony of *Ubaghsia crassa* Lang.
3F	70	0.35	Very rarely seen, yellow chalk; has yielded *Echinocorys*.
4F	100	0.50	White chalk with grey streaks and *Belemnitella*
5F	100	0.50	Yielded a large [flint] ammonite from white chalk with grey streaks.
6F	100	0.50	Not seen. "Upcher groyne" separates 6F and 7F.
7F	140	0.70	Not seen; Lifeboat station at 7F.1
8F	310	1.55	Yellow chalk with abundant sponges and bivalves.
9F	240	1.20	Robin Friend (eastern edge) – Catton Sponge Bed? Yellow chalk.
10F	320	1.60	Robin Friend (western edge) – Catton Sponge Bed? Yellow chalk. **TG 143 436**
WEST	**4.4 km**	**22.0 (m)**	**Totals (rounded).** Adding the extra metre to the top of the section to meet the base of the Paramoudra Chalk would make the thickness 23m.

*The term "thalassinid" has been retained here where Mr. Wood used it in his notes and where the author was confident of his interpretation of the genesis of a flint band.

FRAME CONTENTS

Where a flint band is stated to be at a particular location this relates to the westernmost, leading edge of its base close to LWM. The bands extend diagonally across the beach west to east and from high water mark (HWM) to LWM trending at an angle of about 30 degrees (WSW-ENE) to the coast.

While over 200 taxa are known to occur in the Beeston Chalk, reference will only be made to macrofossils identifiable in the field or to meso-fossils that have important stratigraphical or palaeoecological importance. To collect specimens of the many species present it is necessary to take a large sample of chalk and disaggregate it before sieving out any fossils present and identifying them under a microscope. The extremely soft, pure white chalk in F11 for example is extremely poor in macrofossils but disaggregation and sieving yields a considerable diversity of taxa.

Describing the topology of flint bands accurately and unambiguously without the aid of photographs and excluding personal idiosyncrasies is very difficult. Wood made observations up to Frame 8 and his descriptors have been used with the author's equivalent shown in square brackets afterwards for those Frames for which the author did not have any personal observations. From Frame 9 to Frame 14 the author's descriptors are used.

Frames F1-F2

F1 has not been exposed to the author's knowledge during the past decade; it is present in front of the Two Lifeboats Hotel. According to Peake (pers. comm.) and Mortimore, *et al.* (2001, p. 358) F1 includes the third of the three Catton Sponge Beds known to them. The location of the third Catton Sponge Bed in front of the Two Lifeboats Hotel provides an important 'anchor point' for the SVS.. Even though no detail can be given for the base of the section a thickness for the unseen strata can still be calculated.

F2 was poorly visible to Wood in 1979/81. A possible semi-continuous thalassinid flint band was recorded at F2.8 but very few other details were visible. F1 and F2 are located in front of the 'Driftway'; a storm drain outfall but formerly a (pre-/post-glacial?) stream that excavated a (now largely infilled) channel at this point.

Marker:

Base of thalassinid [labyrinthine] flint band at **F2.8:LWM**, (approximate).

Table 2. Calculated separation between flint bands given in metres and description of main chalk features

Horizon	**Sep. (m)**	**Description**
		MOS: The 'Bone Bed'.
		White nodular chalk with AEH (in nests).
F15.0:LWM	3.06	Massive perforate tabulate flint band incorporating large paramoudras.
		MOS: yellow phosphatic chalk with abundant, worn broken *Echinocorys* tests having a well preserved epifauna, chiefly of bryozoa, especially '*Andriopora' major* Larwood, and common belemnites, many of these very young juveniles.
F12.9:LWM	0.64	Base of massive perforate tabulate flint band.
		MOS: Yellow chalk with AEH consisting of crushed *Echinocorys* in nests with a distinctive epifauna. Medium sized, buff coloured *Pycnodonte* not infrequent, though often bioeroded.
F12.5:LWM	0.48	Base of massive perforate tabulate flint band
		MOS: Yellow chalk with AEH consisting of crushed *Echinocorys* in nests with a good epifauna followed by small, jet-black *Pycnodonte*, and a diverse sponge and fish fauna.
F12.3:LWM	1.12	Base of massive perforate tabulate flint band
F11.9:LWM		MOS marked by change from white to yellow chalk followed immediately by an AEH with medium size, crushed *Echinocorys* and small *Galerites* both with good epifauna closely followed by bed of worn brick-red *Pycnodonte*.
F11.5	0.96	Sparse band of cow-pat and metamoudra flints in homogeneous white chalk
F11.0:LWM		MOS: overlain by AEH; well-preserved, medium-size *Echinocorys* with well-preserved, diverse epifauna.
F10.9:LWM		MOS overlain by ABH: abundant guards in various stages of degradation.
F10.9:LWM	1.55	Top of open thalassinid flint band the upper surface of which bears acuminate ridges. The band also incorporates burrow-riddled metamoudras.
F10.3-F10.9:LWM		White, pyritic nodular chalk, average nodule size decreasing upwards.
F9.9:LWM	0.62	Massive tabulate band.
F.9.8-F9.9		Yellow chalk with occasional *Echinocorys*, large *Galerites* and gerontic

		Cretirhynchia.
F9.5:- F9.8:LWM		Orben Beck "gravity collapse structure".
F9.5:LWM	0.85	Extrapolated LWM position of massive ring flint commencing at F8.9:HWM in white, pyritic, homogeneous chalk with many sponges.
F8.6:HWM- F8.9:LWM		AEH with large well-preserved *Echinocorys* having a diverse epifauna; rare *Cretirhynchia woodwardi.*
F8.9:LWM	1.24	Thalassinid flint band in white pyritic chalk.
F8.0-F9.0		Firm white pyritic chalk with many sponges.
F7.0-F8.0		Hard to firm yellow chalk with sparse, well-preserved *Echinocorys* band with distinctive epifauna at F7.5:LWM.
F7.3		Abundant corals, (*Parasmilia*), pachydiscid ammonites, (some wholly or partially flint preserved), sponges, *Hyotissa,* rare *Micraster.*
F7.2:LWM	0.93	Gracile, thalassinid flint band; occasional massive turreted flints with carious interiors.
F6.9:LWM		Sharp colour change in chalk from grey to yellow.
F6.8:LWM		AEH: Strong Bed of *Echinocorys* shown by Wood (M.S.).
F6.0-F6.9		Abundant belemnites, *Carneithyris*, *Cretirhynchia*, *Pycnodonte*, *Spondylus*, sponges, abundant low-diversity bryozoan fauna in hard grey chalk with glauconitic pebbles.
F6.0:LWM	0.62	Semi-continuous overgrown thalassinid flint band in nodular, white, pyritic chalk.
F5.1:HWM- F5.5MWM		Grey chalk with belemnites.
F5.0	0.73	Grey ring and thalassinid flints with belemnites.
F4.0-F4.9		White chalk with *Inoceramus.*
F3.5	0.37	Scattered, large cowpat flints in yellow chalk.
F3.0-F3.9		Yellow chalk with *Inoceramus*
F2.8:LWM	1.03	Extrapolated LWM position of thalassinid flint recorded by Wood (M.S.).
F1.0	BASE	No observations made from F1.0-F2.8 but the uppermost of the three Catton Sponge Beds known to Mortimore *et al.* (2001) is recorded as being in F1. It has been given a position of F1.0:LWM to provide a base from which to calculate separations.

Frame F3

A band of large, thick "cowpat" shaped flints with thin cortices often containing fasciculate sponges may occasionally be seen at F3.5. Wood records this band as consisting of a "scattered giant form of flattened potstone type". These occur in firm, yellow chalk rich in large fragments of *Inoceramus* that often have a very well preserved epifauna. The top of the beach is almost invariably sand covered.

Marker:

Estimated base of flint band at **F3.5:LWM**.

The following taxa are recorded:

Inoceramus sp., Belemnitella sp. There are many other encrusting taxa on fragments of *Inoceramus* shell; these are often well-preserved.

Frame F4

F4 was much better exposed to Wood than it has been to the author and this description relies heavily on his notes. These show a band of large, "grey ring flints and thalassinid flints" at F5.0:LWM, and white chalk with *Inoceramus* and belemnites. This band should disappear at about F5.3:LWM but sand cover prevents confirmation.

Marker:

Base of large, grey ring flints at **F5.0:LWM**.

Wood recorded the following taxa:

Inoceramus sp. and unidentified belemnites (presumably *Belemnitella*) and the sponge *Porosphaera*, (presumably *P. globularis*).

Frame F5

F5 is the lowest Frame in which chalk is routinely, if only partially, visible now. Wood records grey chalk with belemnites across most of the Frame at LWM associated with a strong band of semi-continuous thalassinid [irregular, robust labyrinthine] flint exiting at the end of the Frame (F6.0). Higher up the beach the author records white, nodular chalk with pyrite films on joints and robust labyrinthine flints at F5.2:HWM, this band appears to extend to F6.0:LWM. The chalk contains abundant sheets of *Inoceramus* shell

fragments. Wood records a bed of *Echinocorys* from F5.4:HWM-F6.8:LWM. The eastern end of the Frame between MWM and HWM is not often exposed today.

Marker:
Semi-continuous thalassinid [irregular, robust labyrinthine] flint band at **F6.0:LWM**.

The following taxa have been recorded:
Inoceramus, *Belemnitella* and *Echinocorys*.

Frame F6

Wood records a bed of *Echinocorys* entering at F6.0:MWM exiting at F6.8:LWM, (the continuation of that in F5), and a flint band starting at F6.0:HWM, and by extrapolation exiting at F7.2:LWM, above which belemnites and brachiopods are recorded. The whole beach appears to be underlain by a semi-continuous thalassinid [gracile labyrinthine] flint band; in fact this is the end of the last flint band in F5 overlapping the outcrop of the new band at F6.0:HWM. Wood's notes clarify where the base of each unit should be taken. This has long been difficult to determine as erosion has removed so much chalk above and between the bands. The situation was further exacerbated by the accumulation of sand arising from repairs and extensions to the sea defences.

F6.0-F6.9 is filled with hard grey chalk with glauconitised pebbles. It yields abundant belemnites, large brachiopods, (*Cretirhynchia arcuata*, *C.* aff. *woodwardi*, *Carneithyris carnea*), and sponges, encrusting serpulids, bryozoa and bivalves. Brachiopods are larger and more plentiful here than at any other horizon examined in the Beeston Chalk on the coast. *Cretirhynchia* aff. *woodwardi* is rather scarce here, having previously been thought to be restricted to below the CSB's (Wood, 1988, p. 65). Specimens from F6 include individuals exhibiting a markedly asymmetrical linguiform extension to the pedicle valve, a feature that is prevalent in its much larger descendant species *C. magna* from the Lower Maastrichtian of Sidestrand.

Common sponge encrusters are *Pycnodonte vesiculare* with frequent *Spondylus dutempleanus*; both have black shells here, (attributed to finely dispersed pyrite permeating the shell structure). The former is frequently found detached from its original substrate with its attachment scar covered in encrusting juvenile bivalves (also often *Pycnodonte*), bryozoa and serpulids. Bryozoa are common in this Frame, but not very diverse, (mainly species of *Stomatopora*, "*Berenicea*", "*Membranipora*", *Callopora*,

Dionella, Ellisina, 'Andriopora' gen. et sp. nov., Pancheilopora sp. nov. and occasional *Castanopora sp. ?nov.*), may reach a large size, and usually encrust sponges, *Pycnodonte* and belemnite guards. Erect, fan-shaped colonies of the bryozoan *Retepora* may also be found; these were attached to substrata that kept them above the sea floor.

F6.5-F6.9 has yielded some *Cardiaster cordiformis* (Woodward, 1833). The author found *Echinocorys* to be rare from F6.5 to F6.9, of moderate size, with round bases and somewhat conical. In that respect this site is somewhat similar to the Sponge Beds at Sidestrand, which yield conical *Echinocorys* and *Cardiaster granulosus* (Goldfuss, 1829). The scarcity of *Echinocorys* is probably an artefact of erosion and exposure. Wood's earlier notes (1970s) show a strong bed from F5.4:HWM to F6.8:LWM, but explicitly recorded the absence of this bed in his later notes. A not dissimilar phenomenon occurs with other "marker" taxa along the coast, e.g. the quixotic "abundance" of brick-red and black *Pycnodonte* at F12.3 and F12.5. The regular echinoid *Salenia* also occurs here, although these are usually broken.

At F6.9:LWM the chalk changes colour very abruptly from grey to bright yellow. The yellow chalk contains common sponges, some gerontic rhynchonellids (*Cretirhynchia norvicensis*), fewer belemnites, some very large solitary corals, e.g. *Parasmilia cylindrica* Milne-Edwards and Haime. Occasional specimens of the oyster *Hyotissa semiplana* occur at or above F6.9 and may be very large. From their attachment scars it may be deduced that their substrates included inoceramids and large ammonites. They frequently bioimmured stalked-cirripedes (e.g. '*Stramentum' sp.*) and these are beautifully preserved as a result. This oyster had previously been thought to characterise the higher part of the Weybourne-3 Chalk.

Markers:

Strong bed of *Echinocorys* at F6.8:LWM

Abrupt change from grey to yellow chalk at F6.9:LWM.

Frame F7

The chalk is hard and yellow across Frame 7. A thalassinid [gracile/slender labyrinthine] flint band commencing at F6.0:HWM is present under most of the western end of the Frame and exits at about F7.2:LWM. A second band of thalassinid [gracile/slender labyrinthine] flints commences late in the Frame at F7.5:HWM and extends to F8.5:LWM. Their true topology may not be represented by these observations as large,

cowpat flints are found around the end of the groyne at F8.0; if these had sinuous ridges on their upper surfaces originally their identity with the "thalassinid" band would be clear. Scouring action is always more intense around the seaward end of groynes and there may be depressions over a metre deep centred there. Huge flints up to 70 cm across are found on the beach which when found broken reveal a carious centre. These often have rings of turrets up to 10 cm high on their base and summit.

A sparse band of domical *Echinocorys* extends to F7.5:LWM. These are often large, well-preserved and with a diverse and dense epifauna of generally well-spaced recruits, mainly bryozoa but including many *Pycnodonte*. These are the result of repeated spatfalls of different taxa that died from within a few hours to a week of recruiting onto the substrate. Only very rarely are adult *Pycnodonte* or large colonies of bryozoa found. The high diversity thus appears to be an artefact; it testifies to the tests being present on the sea floor for an extended period during which they suffered little mechanical damage. *Pycnodonte* is noteworthy for the fact that individuals always orientate themselves in the same alignment relative to their substrate on recruitment. Movement of the substrate in between successive spatfalls is thus easily detectable. They attach to the substrate when the larva settles and cements what becomes their left valve to it. They are also highly gregarious. Up to five discrete spatfalls of the bivalve *Pycnodonte* have been identified on a single *Echinocorys* test. The individual recruiting first reached the largest size (~5 mm) and was followed by four successive recruitments to the exact same location and orientation, each *within* the preceding individual's extant, cemented shell, (the uncemented right valve having fallen off *post mortem*). Equating size to length of survival reveals a picture in which conditions were steadily deteriorating. This "Russian doll" pattern of recruitment is not known to occur elsewhere in the ENC.

The site has yielded a single specimen of a *Micraster*.

The site occasionally produces medium-large size pachydiscid ammonites, some of which are wholly or partially preserved in flint. The maximum diversity of the fauna is almost immediately above the point where the chalk changes from grey to yellow, (F6.9-F7.2).

Marker

Base of thalassinid [slender labyrinthine] flint at **F7.2:LWM**.

Sparse bed of large unworn *Echinocorys* with a distinctive epifaunal recruitment pattern at F7.5:LWM.

Frame 8

All of the chalk in this Frame is white. The thalassinid flint [slender labyrinthine] band that commenced in F7 enters at F8.0:MWM exiting at F8.4:LWM; it is apparently overlain by a set of "ring flints" starting at F8.6:HWM, exiting at F9.4:LWM. This horizon includes concentric flint rings, (typically three, more rarely four), usually lacking a central flint and interconnected by sporadically distributed radial flints, ("capstan ring flints") which are integrated into the rest of the flint band by the continuation of these radial flints. The ring flint is apparently ornamentation on the top of a very substantial tabulate flint band, but routinely poor exposure in the north-west of the Frame [F8.0:LWM] makes it hard to establish the topology of the flint band base.

At F8.0:HWM-F8.4:LWM there is a band of exceptionally soft white chalk that yields abundant belemnites many of which have aragonitic preservation of the alveolus and preservation of the siphuncle. There are very few other fossils at this horizon apart from the hemichordate *Rhabdopleura* represented by its "black stolon" and some encrusting bryozoa, (e.g. *Dionella trigonopora* (Marsson)). Preservation of guards is often excellent, but specimens exhibiting every stage of disintegration by contemporaneous biological agents are present. At F8.1:HWM a very large, chalk preserved (~70 cm) pachydiscid ammonite was visible intermittently for several seasons.

Above the ring flint, the chalk is firm, white and homogeneous and contains much pyrite mostly as discrete nodular masses. These are often fossil sponges or other colonial or solitary benthic invertebrates that often have a diverse epifauna, (articulate brachiopods that must have been anchored by their pedicles, bryozoa and bivalves). The nodules are often some tens of cm across and their large size protected their epifauna from compaction: byssally attached bivalves are still present with their valves in intimate association, spinose bivalves such as *Spondylus dutempleanus* retain unbroken spines and large segments of arborescent bryozoa survive intact.

Immediately above the ring flint horizon (F8.6:HWM-F8.9:LWM) there is a bed of large, well-preserved *Echinocorys* with an excellent and diverse epifauna of inarticulate (*Ancistrocrania*, *Discinisca*), and articulate (*Bifolium*) brachiopods and bivalves, (*Atreta*, *Pycnodonte* – mostly young individuals of the latter), a very diverse suite of bryozoa and several serpulids as well as the hemichordate *Rhabdopleura*.

This Frame has provided a specimen of the brachiopod *Cretirhynchia woodwardi.*

Markers:

Flint band at **F8.6:LWM**.

Bed of large *Echinocorys* with large fragments of *Inoceramus* in firm, white, unwinnowed chalk at F8.9:LWM

Frame 9

The chalk across this Frame is hard and yellow at the eastern end, firm to hard and white at the western end. A belt of reconstituted chalk and diamicton interrupts it where Orben Beck flows out across the beach. This appears to be a gravity collapse structure, (see **Problems** above). At the far end of the Frame, a massive tabulate flint band starts at F9.9:LWM and continues to F10.3:LWM. A hump of sand is almost permanently present along the middle of the beach between the LWM and HWM.

The upper surface of the flint band entering the Frame from F8 is marked with "pseudo-sutures": sinuous lines around flints, especially where there are outgrowths. These indicate that the flint grew in two phases: an initial phase in which an open gracile labyrinthine band formed, segments being united at nodes, followed by a second phase of growth centred on the nodes. The junction between the two appears as a sinuous line across a segment but fractures cutting these "pseudo-sutures" reveal no obvious junction. This flint band should reach LWM in the vicinity of the gravity collapse structure at F9.5:LWM.

At F9.5:MWM white chalk with pyritic fossils occurs as in F8.
Echinocorys, *Galerites*, *Hagenowia* and large rhynchonellid brachiopods, *Cretirhynchia norvicensis* Pettit and *Neoliothyrina obesa* Sahni occur at the eastern end. A heteromorph ammonite, "*Bostrychoceras?*" also occurs.

Marker

Massive rounded overgrown labyrinthine band with "pseudo-sutures" at **F9.5:LWM** [extrapolated from outcrop at F9.3:MWM].

Massive tabulate flint band with rounded nodular upper surface at **F9.9:LWM.**

Frame 10

The massive tabulate flint band at F9.9:LWM tails off and disappears at F10.3:LWM. The chalk becomes white, nodular, in places pyritic. The size of nodules decreases abruptly at several points across the Frame until the base of a very open thalassinid flint band is reached with an upper surface covered by sharp, acuminate ridges. This band also incorporates massive isolated flints riddled with borings (metamoudras) at F10.9:LWM. Above this is a MOS with an ABH followed by a bed of moderately sized, usually complete, unworn and uncrushed *Echinocorys* with a diverse, mature epifauna in firm white chalk.

Pyrite routinely preserves sponges and their associated epifauna and occasionally preserves isolated gastropods, (~1 cm tall). Large (10 x 15 x 30 cm) rounded massive calcisponges, (*Pharetrospongia spp. s. l.*), first appear here in relative abundance (although they are known from a single specimen in F7) and continue as a minor element of the fauna up to F13.

Markers

Nodular chalk beds

Open thalassinid flint with upper surface covered by acuminate ridges at **F10.9:LWM**.

ABH above MOS above flint band.

AEH above ABH.

Frame 11

The flint band at F10.9:LWM disappears by about F11.3:LWM; there is a sparse band of large isolated cowpat flints at about F11.5:LWM. The chalk from F11.0-F11.9:LWM is firm-soft, white and homogeneous. The macro-fauna is very sparse apart from a few belemnite guards. Bulk samples from F11 yielded a diverse meso-fauna including rostra of the irregular echinoid *Hagenowia.* At F11.9:LWM the chalk changes in colour abruptly from pure white to bright yellow marking a MOS followed by an AEH. Abundant *Echinocorys* and small (25 mm) *Galerites* are present in life position. They are too crushed to collect whole, but test fragments show that they were very worn (presumably by contemporaneous bioerosion since they were mostly in life position and orientation) and had been subject to repeated phases of recruitment, mainly by bryozoa: these are often beautifully preserved. The chalk from the interior of the test often reveals moulds of aragonitic fossils; current action also tended to garner fossils into the tests'

interiors. A little above the AEH (probably about F12.2:LWM) there is a band of small to medium sized, brick-red *Pycnodonte*. These usually show evidence of intense *pre* and *post mortem* damage.

Markers

Band of sparse cowpat flints and metamoudras at **F11.5:LWM**.
Sharp colour change in chalk at MOS
AEH above MOS and associated brick-red, worn, *Pycnodonte*

Frame 12

Firm yellow chalk remains consistent across the Frame, except where affected by Pleistocene diagenetic processes that disrupt its structure or cause local intense hardening. A massive perforate tabulate flint band entering from F11.8:HWM continues to about F12.2:LWM and incorporates large (1.5 m diameter), erratically occurring and well-isolated individual ring flints. Another massive perforate tabulate flint band commences at F12.5:LWM, but east of this point the picture becomes confused. There appears to be another massive perforate tabulate flint band at or about F12.9:LWM that extends to F14.1:LWM, (discussed earlier in **Problems**).

The AEH from F11.9:LWM (described above) extends into F12; another MOS with an AEH is present above the perforate tabulate flint band at F12.5:LWM where small crushed *Echinocorys* occur mainly in current garnered "nests". This also appears to be true of an AEH at F12.9:LWM but it has a stratigraphically distinctive bryozoan epifauna. The AEH at F12.5 is further characterised by the presence of small, jet-black *Pycnodonte*, large specimens of the corals *Coelosmilia laxa* and *Moltkia*, sponges, a diverse suite of large and sometimes erect bryozoan colonies and by a marked increase in the abundance and diversity of fish. Bulk samples from F12.5 yield rostra of the irregular echinoid *Hagenowia*. These three MOS's are here designated the Old Butt's Lower, Middle and Upper MOS's.

Markers

Massive, perforate tabulate flint band at **F12.2:LWM** followed by bed of brick-red Pycnodonte from F11.9:HWM to F12.3:LWM.
Massive, perforate tabulate flint band at **F12.5:LWM** followed by an AEH with "nests" of crushed *Echinocorys* and jet-black *Pycnodonte*.

Massive, perforate tabulate flint band at **F12.9:LWM** associated with an AEH with nests of crushed *Echinocorys* and medium to moderately large-sized buff-coloured *Pycnodonte*, the latter often much bored by algal and fungal meshes. This site contains the first occurrence of a new species of the encrusting bryozoan genus *Ubaghsia*. This genus, represented inland by the species *U. crassa* Lang, is common throughout most of the 'Norwich Chalk'. The new species found on the coast does not appear inland until the Upper Paramoudra-2 Chalk at Whitlingham and continues into the Lower Maastrichtian "White Chalk without *'Ostrea' lunata*" at Trimingham, although it is briefly displaced by a different species, *U. reticulata* in the slightly older *Porosphaera* Beds at Sidestrand. The genus is virtually unknown on the coast at lower horizons in the Beeston Chalk except for one tiny abraded colony fragment from 2F near the base of the Member.

Frame 13

A massive tabulate flint incorporating paramoudras the same height as the band's thickness extends across the width of the Frame on into F14.1:LWM where it finally disappears. The band is embedded in yellow chalk also visible at HWM. Towards the east, the chalk becomes more phosphatic and orange-yellow, containing abundant chocolate-brown and pink phosphatic granules at HWM.

Belemnite guards are fairly common, and calcisponges (*Pharetrospongia spp.*) occur too, often with an epifauna of bryozoans. Large and often irregular specimens of the sponges *Porosphaera globularis* and *P. sessilis* occur. *P. sessilis* normally grows as low, circular, disciform colonies on the seafloor. Specimens consisting of stacks of low domical discs provide evidence of low sedimentation rates and varying direction and the gentleness of current action responsible for wafting minor amounts of chalk onto their edge. Colonies thus affected grew out over the chalk to create a new disc-shaped colony on the sea floor attached to the previous or founding part. To the east, at the top of the beach, specimens of the solitary coral *Coelosmilia granulata* occur, their calyxes often penetrated by a network of tiny borings, possibly commensal hydroids.

Marker

F13.9:HWM entry of phosphatic chalk.

Frame 14

The end of the flint band in F13 just makes it to F14.1:LWM to be followed by a MOS above which is an expanse of yellow phosphatic chalk containing nests and individuals of worn and broken *Echinocorys* tests that can have a very well preserved epifauna. In particular, the site yields large colonies of a distinctive form of the cribrimorph bryozoan '*Andriopora' major* Larwood and abundant very young juvenile guards of *Belemnitella.* This MOS is designated here the Water Lane MOS. It is not named as part of the Old Butts sequence of MOS's because the relationships are not yet clear across F13.

Markers

MOS followed by AEH with worn, broken tests having a distinctive epifauna.
Massive flint band with paramoudras at **F15.0:LWM.**

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GLOSSARY

CSB	The Catton Sponge Bed(s) are a series of major hardgrounds of which there are now known to be at least four. The terminal erosion surface of the second CSB marks the top of the Weybourne Chalk.
CSE	Caistor St. Edmund chalk pit; this shows the only remaining substantial inland exposure in the Beeston Chalk.
ENC	"East Norfolk Chalk": an informal abbreviation referring to the upper Upper Campanian and lower Lower Maastrichtian outcrop and subcrop of the Chalk in eastern Norfolk.
F	Abbreviation for "Frame": the interval between two consecutive groynes (or equivalent permanent linear marker features) along the beach.
"Metamoudras"	Large flints of approximately the same size as paramoudras but lacking any obvious central burrow or overall barrel shape. These may be riddled with burrows other than *Bathichnus paramoudræ*.
"Nests"	The earlier literature makes frequent references to "nests" of *Echinocorys* tests. The tests are usually crushed and broken with varying degrees of wear to the surface sculpture. These are current garnered tests of dead individuals that have been swept into scour hollows produced during an earlier phase of intense turbulent current flow. They are thus primarily a sedimentary and taphonomic rather than biological phenomenon. Nonetheless, although severely damaged, these tests constituted an important spatial refuge for many benthic taxa and provide information about the palaeoecology that would not otherwise be preserved.
Norwich Chalk	In essence, the 'old' zone of *Belemnitella mucronata* s.l. in the county of Norfolk. Now more strictly correctly referable to as the upper Upper Campanian zones of *B. mucronata* s.s. to *B. minor II* subsp., (in practice up to the base of the Maastrichtian).
SVS	Synthetic Vertical Section: a section produced from measurements made on a horizontal outcrop and transformed by the application of simple trigonometry into a representation of vertical strata using knowledge of the dip and strike of the beds.

APPENDIX A

Catalogue numbers for specimens in the author's collection have a four-part format:
Site code (sub-site code) species number/specimen number

The **site code** is mandatory and is a unique 2-3 rarely 4 letter abbreviation of the site name, e.g. "SGH" for Sheringham. The **sub-site code** is also mandatory and its meaning can be found by reference to the catalogue. In practice, it is always enclosed between parentheses. "XY" will almost invariably mean collected from between adjacent reference horizons "X" and "Y" at the site, these in turn will almost invariably prove to be flint bands; "S9" would be sample number 9 from the associated site; "AB:S3" would be sample 3 from between horizons "A" and "B".

A "?" will usually mean that the specimen was found *ex situ*; e.g. "BC?" means there is doubt as to whether the specimen came from between bands 'B' and 'C'. Every usable specimen in the author's collection bears a site and sub-site code. The **species number** refers to an identification made and is allocated in sequence as specimens are identified from each site. This may happen some considerable time after they were collected. Hence, species lists are unique to each site. The last number is a **specimen number** and where used (it usually is not) is **always attached** to a **species number**. It is used to record specific information about **one** particular specimen that is in some way special enough to justify doing so. Only specimens that *use all four parts* of the catalogue number have a unique catalogue number.

Anyone examining specimens from the author's collection that have been donated to a museum should <u>never</u> "identify" individual specimens they wish to refer to in their research by augmenting the author's catalogue number. If the author has included only the compulsory elements of the site code then (e.g.) adding a "1" implies an association with an identification with species "1" in the author's catalogue or worse. The museum should ***always*** be required to supply one of its ***own*** catalogue numbers. (Specimens donated by the author to a museum have been published in Smith & Wright (1990) – with unofficially augmented catalogue numbers.)

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THE POSTWICK GROVE RIVER CLIFF SECTION AND THE STRATIGRAPHY OF THE UPPER PARAMOUDRA CHALK

Paul S. Whittlesea

8 Eaton Old Hall, Hurd Road
Norwich, NR4 7BE

ABSTRACT

The fauna and river cliff section at Postwick Grove is described and its stratigraphic position re-evaluated. The Paramoudra-2 Chalk of Wood (1988) is split into two sub-units: the Paramoudra-2A Chalk and Paramoudra-2B Chalk. It is recommended that Postwick Grove be considered for SSSI status.

INTRODUCTION

The section in the river cliff at Postwick Grove (TG 286 080; Fig. 1) is the most easterly, extant, permanent inland exposure of the Norfolk Chalk. Stratigraphically, it is known to expose a richly fossiliferous horizon very high in the uppermost Campanian, close to the boundary with the overlying Maastrichtian. This makes it of exceptional biostratigraphical interest both nationally and internationally and has recently (late May 2003) prompted a visit by the Vijlen Group from Belgium. Although known since at least the early part of the 19th century no published formal description or log exists for the section.

Previous research

Since the 19th century Postwick Grove has been well-known to collectors of local Chalk fossils for its "cast beds" that contain originally wholly or partially aragonite-shelled molluscs (bivalves, scaphopods, gastropods and ammonites) preserved as paired internal and external moulds in hard chalk (Woodward, 1833, Lyell, 1840). This lithology is now recognised as being associated with hardground formation (Kennedy & Garrison, 1975). Many specimens, both of calcitic fossils and of moulds collected from the site by the author are kept by Norwich Castle Museum. However, research on the palaeontology of

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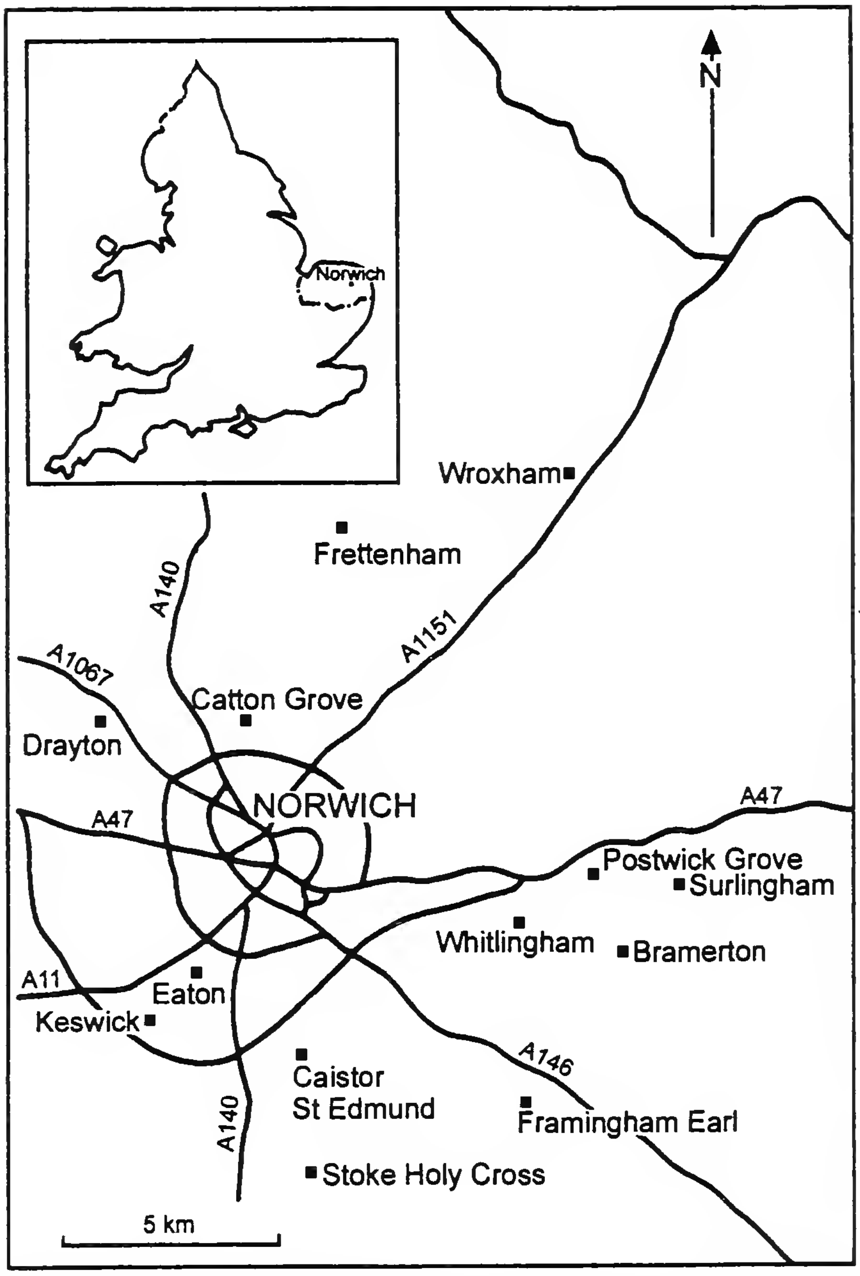

Fig. 1. Locality map of Postwick Grove site.

these moulds has been neglected and a great deal of taxonomic research remains to be done. In addition, the site has yielded several new bryozoan taxa that await description.

STRATIGRAPHY

Postwick Grove was used by Wood (1988) as one of the key sites for describing the Paramoudra-2 Chalk (Fig. 2). The other sites listed by Wood (1988) have since become overgrown or obliterated. The Paramoudra-2 horizon as defined by Wood (1988) is the highest unit of the Campanian preceding the Maastrichtian, and its facies and fauna are therefore of considerable interest. Since this site currently provides the last remaining exposure at this horizon, it should be considered urgently as a candidate for SSSI status.

SECTION

The section described here (Fig. 3 and Table 1) was seen by a party from the Geological Society of Norfolk during a field meeting in the 1990s to clear the scree and excavate beneath the level of the water meadow in front of the river cliff. The total thickness of section seen was just over 6 m, but 2 m had to be backfilled afterwards as a condition of visiting the site. Since the lower parts of the section were exposed only for one afternoon, details of the lithology and fauna from this part are unavoidably less detailed. The land in front of the site is no longer maintained for live-stock, and the site now needs to be cleared of scree and vegetation every five years.

The section contains at least two and possibly up to five repeating units consisting of:

1. Thin, laminated, clay-rich allochthonous chalk (debris flow deposits)
2. Orange-yellow mottled chalk
3. Hardground overlying thalassinid burrow systems
4. Thalassinid flints and burrows systems penetrating hardground chalk containing "cast" bed(s)
5. Soft, crumbly white allochthonous chalk

Wood (1988, p. 95) had already suggested that this sort of succession is repeated many times in the Paramoudra-2 Chalk and these data support this speculation. The white chalk at the base of the 6 m section may belong to the uppermost Paramoudra-1 Chalk.

The porcelainous layer at the top of the section is interpreted as a diagenetically hardened surface, (i.e. probably post-Cretaceous). The hardground surfaces are gently undulating with relatively little relief. They are penetrated by thalassinid burrow systems into which softer chalks have been piped down and / or thalassinid flints have formed. The laminated allochthonous chalks (beds C and H) are closely spaced sequences of thin (typically ~1-2 cm) chalks with swirling texture picked out by being relatively clay-rich. Wood (1988, p. 76) referred to these as "...semi-laminated 'buttery' chalk..." They are interpreted as being low-energy current-flow deposits. In the lower of these laminated autochthonous chalk sequences, current energy was apparently sufficient to invert *Echinocorys* tests. The presence of *Echinocorys* in normal life orientation above and below indicates that the position of the inverted tests at the junction of beds G and H (Fig. 3) is not due to glacio-tectonic overturning.

Peake & Hancock (1961) "faunal belts"	**Wood (1988)**	**Johansen & Surlyk (1990) Lithostratigraphy**	**Whittlesea (this paper)**
Paramoudra Chalk	Paramoudra 2 Chalk	Paramoudra Chalk Member	Paramoudra 2B Chalk
			Paramoudra 2A Chalk
	Paramoudra 1 Chalk		Paramoudra 1 Chalk
Beeston Chalk	Beeston Chalk	Beeston Chalk Member	Beeston 3 Chalk
			Beeston 2 Chalk
			Beeston 1 Chalk
Catton Sponge Beds (2)*	Catton Sponge Beds (3)*	Catton Sponge Beds	Catton Sponge Beds (4)*
Weybourne Chalk	Weybourne 3 Chalk	Weybourne Chalk Member	Weybourne 3 Chalk
	Weybourne 2 Chalk		Weybourne 2 Chalk
	Weybourne 1 Chalk		Weybourne 1 Chalk
Eaton Chalk	Pre-Weybourne 5 Chalk	Eaton Chalk Member	Pre-Weybourne 5 Chalk
	Pre-Weybourne 4 Chalk		Pre-Weybourne 4 Chalk
	Pre-Weybourne 3 Chalk		Pre-Weybourne 3 Chalk
	Pre-Weybourne 2 Chalk		Pre-Weybourne 2 Chalk
Basal *mucronata*	Pre-Weybourne 1 Chalk	?	Pre-Weybourne 1 Chalk
5 units	**11 units**	**5 members**	**14 units**

Fig. 2. Stratigraphy of the Norwich Chalk (Campanian) modified from Whittlesea (2006).

*The Catton Sponge Beds are a series of major hardgrounds that straddle the junction between the Weybourne and Beeston Chalks. They are not a biostratigraphic unit in their own right although Johansen & Surlyk (1990) accord them member rank in their lithostratigraphy. Peake & Hancock (1961) initially recognised two sponge beds at the stratotype. Wood (1988) subsequently identified a third lower in the sequence there, and Peake & Hancock (2000) reported four at Castle Mall, Norwich, the newest being at the top of the sequence. The terminal erosion surface of the second hardground from the base marks the top of the Weybourne Chalk.

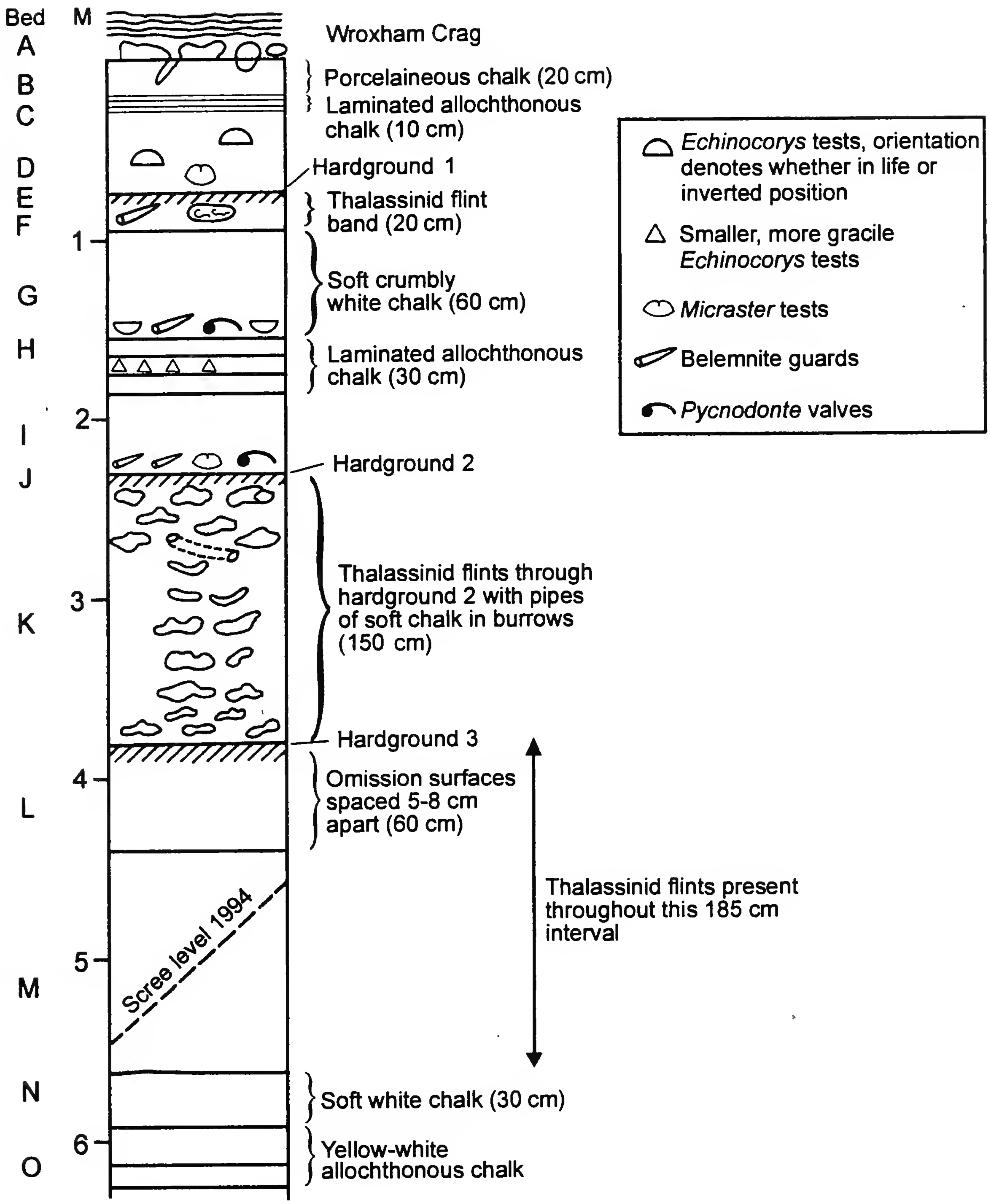

Fig. 3. Graphic log of the Paramoudra-2A Chalk at Postwick Grove river cliff.

Table 1. Postwick Grove measured section.

	Description	Thickness (m)	Sum (m)
A	Fossiliferous, cross-bedded sands of the Wroxham Crag Fmn on hardened chalk surface with barnacles encrusting flints. Flints <35 cm, nodular, sub-aerially weathered, brown patinated, some *in situ* on the chalk surface.	(>1.0)	
B	Diagenetically hardened (post-Cretaceous) porcelaineous chalk	0.20	0.20
C	Laminated allochthonous chalk.	0.10	0.30
D	Mottled orange/yellow crumbly chalk with large, worn, thick-tested, domical *Echinocorys* identical to those at the very top of the former Pound Lane pit, (TG 2755 0900) now a Sainsbury's Superstore. This horizon has also yielded a *Micraster* species.	0.45	0.75
E	Hardground 1		
F	Thalassinid flint band with thin white cortices, jet-black interiors, carious surfaces where "scuff-marked" by intersection with trace fossils in surrounding chalk.	0.20	0.95
G	Mottled orange/yellow crumbly chalk.	0.60	1.55
H	Laminated allochthonous chalk overlain by crushed inverted *Echinocorys*, containing small *Echinocorys* and small *Pycnodonte*.	0.30	1.85
I	Mottled orange/yellow crumbly chalk	0.45	2.30
J	Hardground 2 with *Belemnitella*, *Micraster* and *Pycnodonte*		
K	Thalassinid flint band some showing bright blue vivianite on joint surfaces, brown where this has oxidized; flints commonest in the top 70 cm, **metamoudras present every 1-2m across the section. Where thalassinid burrows are not infilled with flint they may have soft white chalk piped down into them from the surface above.	1.50	3.80
L	*Firm yellow-white chalk with omission surfaces spaced 5-8 cm apart	*0.60	4.40
M	*Firm yellow-white chalk	*1.25	5.65
N	Soft white chalk	0.30	5.95
O	Yellow-white allochthonous chalk	0.20	6.15
	Base of section.		

Notes for Table 1(opposite)

*Thalassinid flints present throughout units 'L' and 'M'. Many of the macrofossils, (e.g. *Carneithyris*, *Pycnodonte* and *Belemnitella*), show cryosolution features.

**Metamoudras are large flints of paramoudra size but lacking an obvious central burrow or overall barrel shape. These may be riddled with burrows other than *Bathichnus paramoudræ*. They typically occur within or just above another flint band.

The fine fabric of the laminated allochthonous chalks (bed H; Fig. 3) can only be seen well when it has been exposed long enough to dry it out, but not so long as to become colonised by fungi, algae, etc. – typically about 6 months. The *Echinocorys* tests in this bed are smaller and thinner than the large, thick-tested domical specimens from bed D and have since disintegrated. Chalk sampled from immediately below, within and above the laminated allochthonous chalks (beds G, H and I) were disaggregated to compare their meso- and macrofauna. However, no meaningful distinction could be discerned.

DISCUSSION

Having investigated the upper Paramoudra-2 Chalk at temporary sections at Whitlingham sewage farm (Whittlesea, 1991) and the lower Paramoudra-2 Chalk at Postwick Grove, it is clear that they are represented by two distinct lithofacies that contain different faunas. The top of the older horizon, well represented at Postwick Grove, is described in this paper. An extensive faunal list was provided for the younger horizon at Whitlingham (Whittlesea, 1991).

The older unit is here defined as the Paramoudra-2A Chalk and the younger unit as the Paramoudra-2B Chalk (Fig. 2). The whole of the Paramoudra Chalk belongs to the zone of *Belemnitella minor* subsp. II. Hence the belemnites, although obvious, do not help establish an identifiable horizon within the Paramoudra Chalk, although *B.* ex gr. *langei/najdini* is supposed to be more prevalent higher in the succession (Christensen, 1995, fig. 2).

The Paramoudra-2A Chalk consists of (mainly) hard yellow chalks incorporating multiple hardgrounds, "cast" beds and thalassinid burrow systems and flints with abundant thick-tested *Echinocorys* ex. gr. *belgica*, *Micraster* aff. *ciplyensis*, *Belemnitella minor* subsp. II, *Pycnodonte vesiculare* and *Carneithyris* aff. *carnea/subcardinalis* as

well as the diverse (>100 species) macrofossil and mesofossil fauna listed (Appendix 1). The presence of frequent hardgrounds, apparent debris flow deposits ("turbidites") and the robust fauna testifies to a high energy, and by inference, shallower water environment.

The Paramoudra-2B Chalk consists of feebly cemented, soft, friable white chalks, that contain fewer flints than the Paramoudra-2A Chalk, although small thalassinid and thick tabulate flint bands and paramoudras do occur. The lithofacies is indicative of an inferred high sedimentation rate in a low energy environment that would have provided a soft unconsolidated substrate. It is largely devoid of obvious macrofossils, but yields an extremely diverse (>165 species) but depauperate mesofauna from disaggregated and sieved samples. There is no single obvious macrofossil or small suite of readily identifiable fossils that can be nominated as 'typical' of this horizon: sampling and comparison with the reference list given by Whittlesea (1991) is essential as several horizons share this lithofacies.

The change in the benthic conditions from Paramoudra-2A to 2B resulted in a change in the bryozoan fauna. Species that needed firm, stable substrates on which to settle and grow, often producing large, robust, erect colonies, were excluded from the soft, weakly consolidated chalk of the Paramoudra-2B. Instead, a fauna with mostly small, vinculariform colonies established itself. These in turn provided a substrate for a diverse suite of micromorphic brachiopods that could recruit onto them; these brachiopods are thus correspondingly common.

ACKNOWLEDGEMENTS

My special thanks go to the landowner, Mr David Langridge and his family for permission to visit the site, to Mr Colin Ellis of Lafarge Aggregates, to Mr Norman B. Peake for much fruitful discussion on the Upper Cretaceous of eastern Norfolk and to Mr Christopher J. Wood for a critical review of, and constructive comments on an earlier version of this manuscript.

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APPENDIX 1. FAUNAL LIST

Sponges

Porosphaera globularis (Phillips), *P. sessilis* Brydone, *Aphrocallistes cylindrodactylus* Schrammen.

Corals

Coelosmilia sp. juv. indet., *Moltkia* sp., *Stephanophyllia clathrata* (von Hagenow).

Brachiopods

Aemula inusitata Steinich, *Ancistrocrania parisiensis* (Defrance), *Argyrotheca hirundo* (von Hagenow), *Carneithyris* aff. *subcardinalis* (Sahni), *Cretirhynchia* (*Homaletarhynchia*) *arcuata* Pettitt, *C.* (*C.*) *norvicensis* Pettitt, *Gisilina sp.*, *Isocrania costata* (Sowerby), *Kingena pentangulata* Woodward, *Magas chitoniformis* Schlötheim, *Neoliothyrina* aff. *obesa* Sahni, *Orbirhynchia sp.* nov., *Terebratulina chrysalis* Schlötheim, *T. faujasii* (Roemer).

Bryozoa

Aggregopora sp., *Clinopora sp.*, *Diastopora spp.*, *Eohornera langethalli* (von Hagenow), *Filisparsa sp.*, *Homaeosolen sp.*, *Idmidronea sp.*, *Meliceritella sp.*, *Meliceritites pentagonum* Levinsen, *Pustulopora spp.*, *Siphoniotyphlus sp.*, *Spiropora verticillata* (Goldfuss), *Stomatopora gracilis* (Edwards), *S. irregularis* (Hennig), *Sulcocava sp.*, *Tecatia sp.*, *Tervia sp.*; *Biflustra argus* d'Orbigny, *Callopora invigilata* (Brydone), *Ellisina britannica* (Brydone), '*Membranipora*' *spp.*, '*M.*' *repugnans* Brydone, '*M.*' *scalprum* Brydone, '*M.*' *weybournensis* Brydone; *Aechmella anglica* (Brydone), *Homalostega punctilla* Brydone, *Lunulites pseudocretacea* Håkansson & Voigt, *Onychocella gibbosum* (Marsson),

O. inelegans (Lonsdale), *O. matrona* (von Hagenow), *O. rowei* Brydone, *O. strumulosa* (d'Orbigny), *Puncturiella* cf. *sculpta* (d'Orbigny), *Puncturiella sp.*, *Semieschara hartfordensis* Brydone; *Castanopora sp. indet.*, *Leptocheilopora sp. nov.*, *Phractoporella constrata* (Lang), *Polycephalopora spp.*, *Tricephalopora robusta* Berthelsen; *Cryptostoma corallinum* Brydone, *Bathystomella* cf. *cordiformis* (von Hagenow.), *Frurionella* aff. *cylindrica* Voigt, *F.* aff. *dubiosa* (Levinsen), *Frurionella sp. nov.*, '*Porina*' *craterica* Brydone, *Pachydermopora disticha* (Goldfuss), '*Porina*' *salebrosa* Marsson, *Systenostoma verticillata* Levinsen. [N.B. this list does not include several new bryozoan genera and species.]

Serpulids

Filogranula cincta (Goldfuss), *Glomerula gordialis* (Schlötheim), *Neomicrorbis crenatostriatus* (Münster), *Neomicrorbis subrugosus* (Münster), *Pentaditrupa subtorquata* (Münster in Goldfuss, 1831), *Sclerostyla macropus* (J. Sowerby), *Vermiliopsis fluctuata* (J. de C. Sowerby), *V. dorsolineata* (Nielsen), *Vepreculina sp.*,

Cirripedes

Arcoscalpellum fossula (Darwin), *Arcoscalpellum maximum* (J. de C. Sowerby), *Brachylepas fallax* (Darwin), *Brachylepas naissanti* (Hébert), *Cretiscalpellum striatum* (Darwin), *Verruca prisca* Bosquet.

Crustaceans

'*Callianassa*' sp. [isolated claws]

Bivalves

Acutostrea incurva Nilsson, *Aequipecten sarumensis* (H. Woods), '*Anomia*' *sp.*, *Arca* (?*Barbatia*) *sp.*, *Atreta nilssoni* (von Hagenow), *Gyropleura inaequirostrata* (Woodward), *Inoceramus spp. indet.*, *Limatula decussata* Goldfuss, *Lyropecten campaniensis* (d'Orbigny), *Margostrea alaeformis* (S. Woodward), *Merkelina variabilis* (von Hagenow), *Neithea sexcostata* (S. Woodward), *Plagiostoma sp. indet.*, *Plicatula hantonensis* Brydone, *Pseudolimea granulata* (Nilsson), *Pycnodonte vesiculare* (Lamarck), *Spondylus dutempleanus* d'Orbigny, *Inoceramus sp.*,

Scaphopods

'*Dentalium*' sp.

Gastropods

Cerithium sp., Trochus sp.

Ammonites

Hoploscaphites cf. *constrictus* (J. Sowerby), '*Baculites*' *sp.*, ammonite granulaptychi.

Belemnites

Belemnitella minor Jeletzky subsp. II

Ophiuroids

Ophiomusium subcylindricum (von Hagenow)

Asteroids

Metopaster sp., *Calliderma smithae* Sladen, *Nymphaster sp.*, *Crateraster sp.*

Crinoids

Austinocrinus bicoronatus (von Hagenow), *Bourgueticrinus constrictus* (von Hagenow), *Nielsenicrinus sp.*

Echinoids

Cardiaster sp. indet., *Cidaris sp.*, *Helicodiadema sp.*, *Phymosoma koenigi* (Mantell) [probably not this species], *Salenia*? sp., *Hagenowia sp.*, *Echinocorys* ex gr. *belgica* Lambert, *Micraster* aff. *ciplyensis* Schlüter.

Vertebrates

Centrophorides appendiculatus (Agassiz, 1843), *Cretolamna appendiculata* (Agassiz), *Dercetes sp.*, *Scapanorhynchus subulatus* (Agassiz).

Note: this list does not include many of the aragonitic mollusc taxa preserved as paired internal and external moulds. Fish scales and vertebrae are very common in some samples and the list of vertebrates is thus a minimum.

GEOLOGICAL SOCIETY OF NORFOLK WEBSITE

The Geological Society of Norfolk has a website which can be reached at:

http://www.norfolkgeology.co.uk

Details of GSN activities can be found here including:

- Information on the aims and constitution
- Forthcoming meetings, lectures and fieldtrips
- Details of GSN projects
- Details of GSN publications, including instructions for authors
- Information on significant recent finds
- Hot links to other geological websites

PRELIMINARY INVESTIGATION INTO MONITORING COASTAL EROSION USING TERRESTRIAL LASER SCANNING: CASE STUDY AT HAPPISBURGH, NORFOLK

C.V.L. Poulton, J.R. Lee, P.R.N. Hobbs, L. Jones & M. Hall*

British Geological Survey, Keyworth, Nottingham, NG12 5GG
*email: cpoulton@bgs.ac.uk

ABSTRACT

The methodology and findings of the application of terrestrial laser scanning to monitor coastal erosion are discussed and put into the wider context of coastal erosion and geology. A terrestrial laser has been used in conjunction with a highly accurate differential Global Positioning System (dGPS) to orient the laser survey and obtain point data of cliff and beach surfaces. These data are captured annually to enable the modelling of cliff retreat over time. The conceptual model generated from this research on cliffs south of Happisburgh, Norfolk, are described to illustrate the value of the methodology. Rates of cliff retreat and volume loss have been calculated and an erosion model for Happisburgh has been developed.

INTRODUCTION

On the soft sediment coasts of eastern and southern England, the problem of coastal erosion is an increasingly important issue. This is due to apparent increase in observed rates of rapid coastal change, the heightened public awareness of sea level rise and climate change, and the perceived threat to the existing buildings on, and increased development of the coastal zone.

Coastal erosion is a serious issue for many coastal communities. The consequences to life, assets and the environment can be enormous - especially as owners do not usually receive any form of compensation for the loss of their homes and livelihoods. It is, therefore, important that cliff retreat is measured accurately so that people can plan for life and work in this dynamic environment.

Bull. geol. Soc. Norfolk (for 2006) **56**, 45-64.

The ongoing Slope Dynamics project at the British Geological Survey (BGS) aims to address some of these issues. In this project the influence of geology, geotechnics and climate change on the process of cliff recession is being assessed at twelve test sites around the 'soft rock' coasts of England specifically in Dorset, Kent, Sussex, Norfolk and North Yorkshire (Table 1). These test sites were selected to satisfy the following criteria: (1) natural slopes with little or no engineering remediation, coastal protection or occupation (although some of the sites are affected by adjacent sea defences, or have been defended in the past but have not been maintained, or have failed, e.g. Happisburgh); (2) soft rock geology (clay, chalk etc.) typical of the coastal unit and the geological materials involved; (3) variety of cliff heights; (4) variety of coastal aspects; (5) variety of landslide mechanisms and complexity; (6) variety of geological complexity; (7) likelihood of active landslide movement and recession; (8) reasonable access to the site; and (9) availability of data.

Each studied site comprises approximately 200 to 500 m of coast and contains one or more landslide features. Many of the sites are situated within an area of classic coastal landslides and have a considerable legacy of research, photography, and analysis over several decades (Lee & Clark, 2002).

METHODOLOGY

The coastal sections are surveyed using a variety of remote methods, accompanied by geological mapping and geotechnical probing, sampling, and testing. The principal methods of surveying the cliffs are long-range terrestrial laser scanning, and terrestrial photogrammetry. Surveys are carried out at all the sites annually and the results are processed to provide data for models of coastal recession. The data collected in the field by laser scanning and GPS are entered into a modelling package (GoCad 2.1.3). The resulting computer model enables volume calculations and observations to be made as to the way in which the coast is eroding.

LONG RANGE TERRESTRIAL LASER SCANNING

Laser scanning has been used for a variety of applications such as the monitoring of volcanoes (Hunter *et al.*, 2003), earthquake and mining subsidence, quarrying, buildings, forensics (Paul & Iwan, 2001; Hiatt, 2002) and terrestrial- (Rowlands *et al.*, 2003) and coastal- (Hobbs *et al.*, 2002) landslide modelling.

The Riegl LPM2K terrestrial laser (Fig. 1a) records accurate data for 3D modelling. It has a long- range capability of up to 2 km and a best achievable range finding resolution of around 25 mm. The relative distance, elevation angle and asimuthal angle between the laser and the cliff face are measured semi-automatically in each scan (Fig. 1b) and, once processed, a 3-D surface model can be generated. Multiple scans taken from different aspects (for instance from the beach and cliff top) at the same site are carried out in order to minimise 'shadows' (i.e. areas invisible to the laser). These are later combined in the software so that these shadow areas are minimised and a more accurate and complete 3D image is recorded. For multiple scans, it is important to have at least three common points in each scan to assist with orientation.

Irresolvable shadow areas are surveyed using a roving Global Positioning System (GPS) unit and the point data are added to the 3-D model. Analyses of repeated scans over a regular time interval can accurately determine the rate of recession, the nature of landslide processes and any other morphological changes in the cliff face and beach.

In addition, laser measurements of targets are carried out at some sites in order to track movements of particular landslide features. The key factor in the successful use of long-range laser scanning is the accurate horizontal and vertical position of the instrument and at least one other point (any positional errors are magnified with distance). In most cases, this is achieved with a high quality GPS, which is essential if the 3-D model produced, is to be oriented to national grid co-ordinates and when coastal changes are to be monitored. The laser scanner is not effective where the subject is moving (e.g. water, vegetation), or where the laser is reflected by heavy rain. However, low light level does not present a problem to laser scanning, as it does with photography.

TERRESTRIAL PHOTOGRAMMETRY

Stereo-vertical aerial photography, oblique aerial photography and terrestrial photography have been obtained for geological and geomorphological study and to record individual landslide events more accurately than is possible from topographic maps alone. Such terrestrial photogrammetry is used to back-up the laser scan and to fill-in geomorphological detail if scanning is not possible. The methodology involves overlapping several photographs of the cliff from different aspects and combining them in software to produce 3-D models, panoramic images, and reference images to help interpret the scanning. Calibrated terrestrial and aerial photographs may also be used to 'drape' the 3-D model obtained from laser scanning. A metric digital camera mounted

Table 1. The Slope Dynamics Project locations, geology and physiology.

Location	Geology	Physiology
Happisburgh, Norfolk [TG 38703070]	Till, clays, sands and gravel	Sand beach, rapid erosion rate (formerly defended)
Sidestrand, Norfolk [TG 26603970]	Till, clays, sands and gravel	Large landslide complex, sand beach (undefended)
Weybourne, Norfolk [TG 11204360]	Clays, sands and chalk	Cobble beach, low recession rates, (undefended)
Warden Point, Isle of Sheppey, Kent [TR 01907250]	London Clay	Landslide complex, clay platform (undefended)
Folkestone Warren, Kent [TR 25803840]	Chalk, Gault Clay	Large landslide complex, researching part of the backscarp (partially defended)
Beachy Head Lighthouse, Sussex [TV 58609520]	Upper Chalk	Chalk cliffs and platform subject to undercutting and collapse, chalk debris aprons (undefended)
Aldbrough, Holderness, Yorkshire [TA 25803960]	Till	Slumps and toppling blocks, different till sheets (lithology and geotechnical properties) (undefended)
Speeton Sands, North Yorkshire [TA 14507600]	Speeton Clay, Kimmeridge Clay and till	Slumps and mudflows complex, sand beach (undefended)
Robin Hood's Bay, North Yorkshire [NZ 95300450]	Lias, till	Slumps and mudflows and Lias platform, narrow shingle/sand beach (defences adjacent)
Black Ven, Lyme Regis, Dorset [SY 35409309]	Lias, Gault Clay, Upper Greensand	Large benched landslide complex, mudflows, slumps (undefended)
Stonebarrow Hill (Cain's Folly), Dorset [SY 37909285]	Lias, Gault Clay, Upper Greensand	Slumps, mudflows in upper part (undefended)
Ware Cliff, Dorset [SY 32909122]	Lias, Gault Clay, Upper Greensand	Slipping along Upper Green Sand (defences adjacent)

on top of the laser permits accurate, calibrated images to be produced and draped over the 3-D image while working in the field.

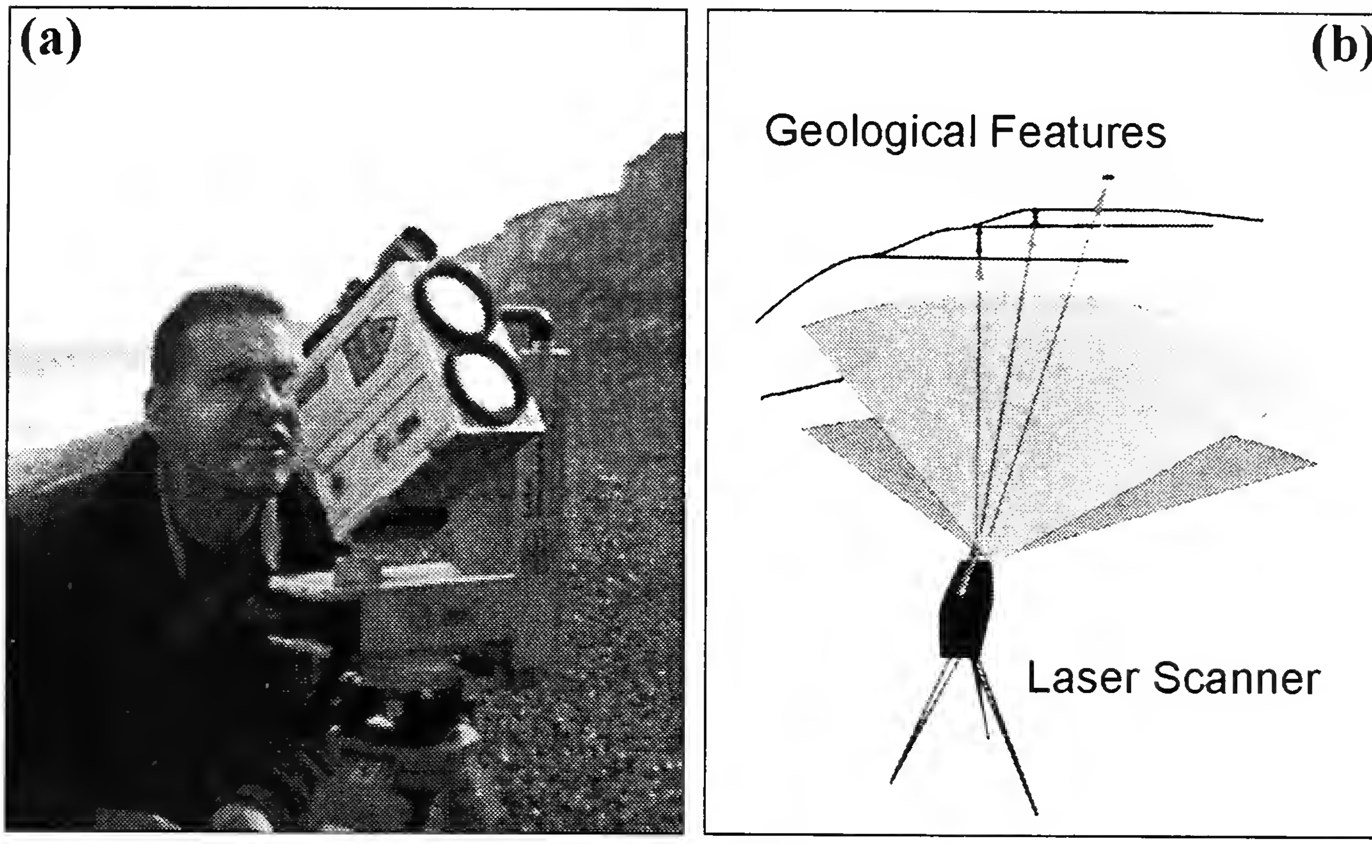


Fig. 1. (a) The Riegl LPM2 K long-range laser scanner © NERC. (b) Schematic diagram to show the laser scan with location of individual points.

ANALYSIS OF COASTAL RECESSION

On fast-retreating coasts it is important to appreciate more than just the position of the cliff face. The entire system of coastal erosion is highly complex and several aspects must be considered. These include the onshore environment, the offshore environment, the weather and climate, the strength and variability of the geological materials making up the coast and the influence of engineered structures such as groynes and sea walls.

Understanding the influence that the offshore environment has on coastal erosion is essential when attempting to accurately model future recession rates. This includes oceanographic climate, wave energy and wave direction, the distribution of sediments moved by wave action and changing sea level. One of the critical factors affecting the rate of erosion is determined by the transport of sediments away from their source – that is, from either the cliffs themselves or from the foreshore, to eventual sediment sinks. Measuring this is a particularly difficult task, especially as coarse materials, such as gravels, may remain in local beach systems, whilst finer materials, such as clays and silts, are readily transported offshore and may end-up being deposited on coasts on the other side of the North Sea (Shennan *et al.*, 2003).

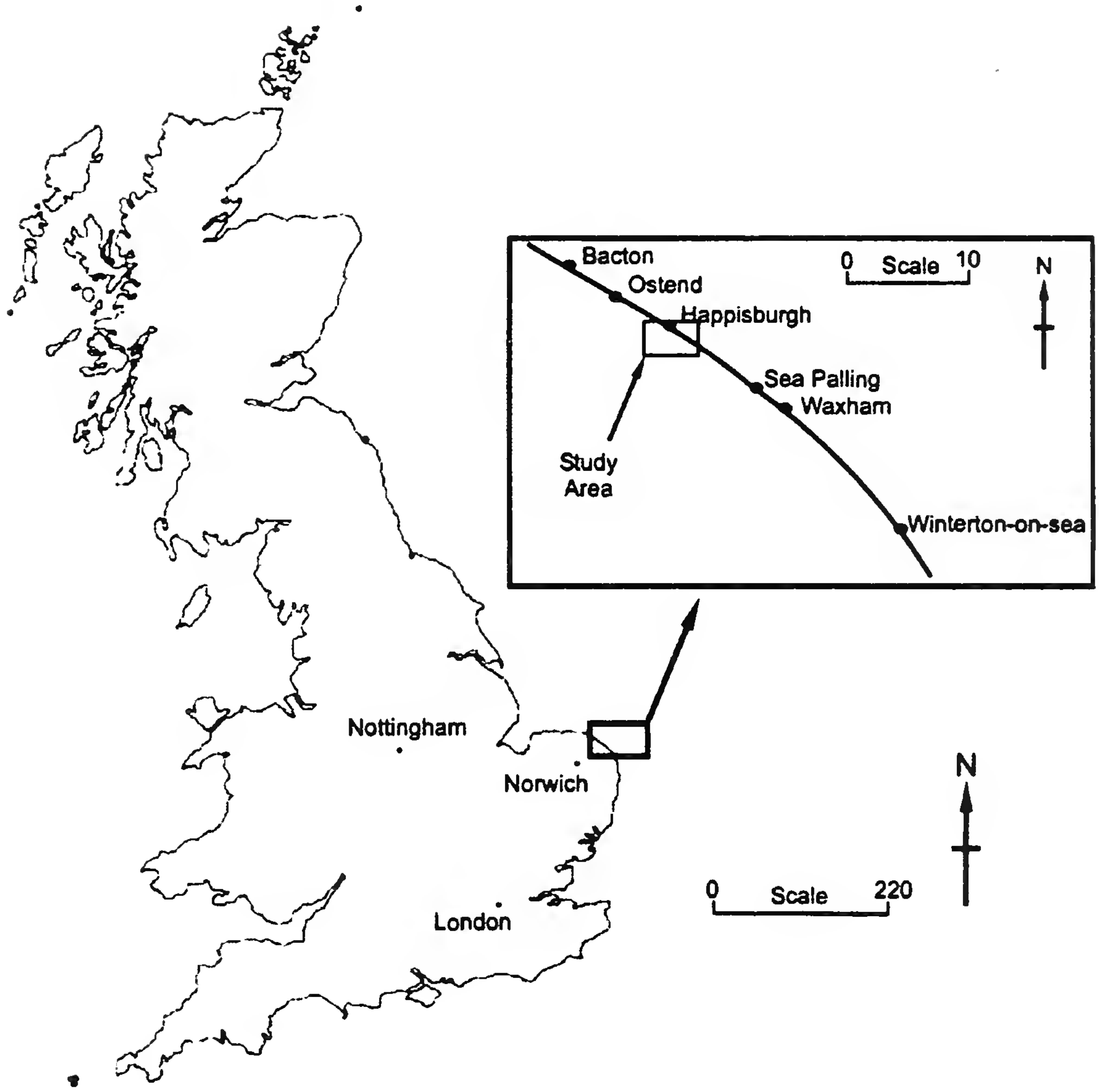


Fig. 2. The East Anglian coastline and study location.

Sea-level rise and climate change are influential factors associated with increased coastal erosion. Current estimates of the relative sea-level rise in eastern England in the 2080s, taking into account isostatic change and different fuel emission scenarios, ranges from 22 cm (assuming a 9 cm global rise with low fuel emissions) to 80 cm (assuming a 69 cm global rise with high emissions) (Hulme *et al.*, 2002).

CASE STUDY – THE EROSION RATE AT HAPPISBURGH

It is likely that the Norfolk cliffs have been eroding at the present rate for the last 5000 years when sea level rose to within a metre or two of its present position (Clayton, 1989). Therefore, the future predictions of sea level rise and storm frequency due to global warming are likely to have a profound impact on coastal erosion and serious consequences for the effectiveness of coastal protection and sea defence schemes in East Anglia in the near future (Thomalla & Vincent, 2003). One of the twelve test sites of the

Slope Dynamics project includes a section of cliffs adjacent to the village of Happisburgh [NGR TG38003100] on Norfolk's North Sea coast, approximately 25 km northeast of Norwich (Fig. 2). Agriculture and tourism contribute significantly to the economy of the village and surrounding hinterland although this is threatened by the receding cliff line that, prior to the construction of a rock bund at the northern end of the survey site, has claimed at least one property per year plus significant quantities of agricultural land (Fig. 3). A section of coast further north of the study location is a designated Site of Special Scientific Interest (SSSI; Fig. 4).

THE GEOLOGY AND PALAEOENVIRONMENTAL CONTEXT OF THE SITE

The cliffs at Happisburgh range in height from 6 to 10 m and are composed of a layer-cake sequence of several tills, separated by beds of stratified silt, clay and sand (Hart, 1987; Lunkka, 1988; Hart, 1999; Lee, 2003). The basal unit within the stratigraphic succession at Happisburgh is the How Hill Member of the Wroxham Crag Formation. These deposits are typically buried beneath modern beach material but are periodically exposed following storms (Fig. 5). They consist of stratified brown sands and clays with occasional quartzose-rich gravel seams that are interpreted as inter-tidal/shallow marine in origin.

Unconformably overlying these marine deposits are a series of glacial lithologies deposited during several advances of glacier ice into the region during the Middle Pleistocene (c.780 to 430 ka BP) (Lee *et al.*, 2002; Lee *et al.*, 2004). The site investigated for the purpose of this study, is located adjacent to Beach Road (Fig. 3; NGR TG38573084) where a tripartite geological succession can be observed. The Happisburgh Till Member, crops-out at the base of the cliffs and its base is frequently obscured by modern beach material: it has a maximum thickness of 3 m. The Happisburgh Till Member is a dark grey, highly consolidated till with a matrix composed of a largely massive clayey sand with rare (<1%) pebbles of local and far-travelled material. The upper surface of the till undulates and comprises a series of ridges and troughs upon which the overlying Ostend Clay member outcrops. This unit is between 2.3 and 3.4 m thick and consists of thinly-laminated light grey silts and dark grey clays. In turn, these beds are overlain by 2 to 4 m, of weak, stratified sand (Happisburgh Sand Member) with occasional silty-clay horizons.

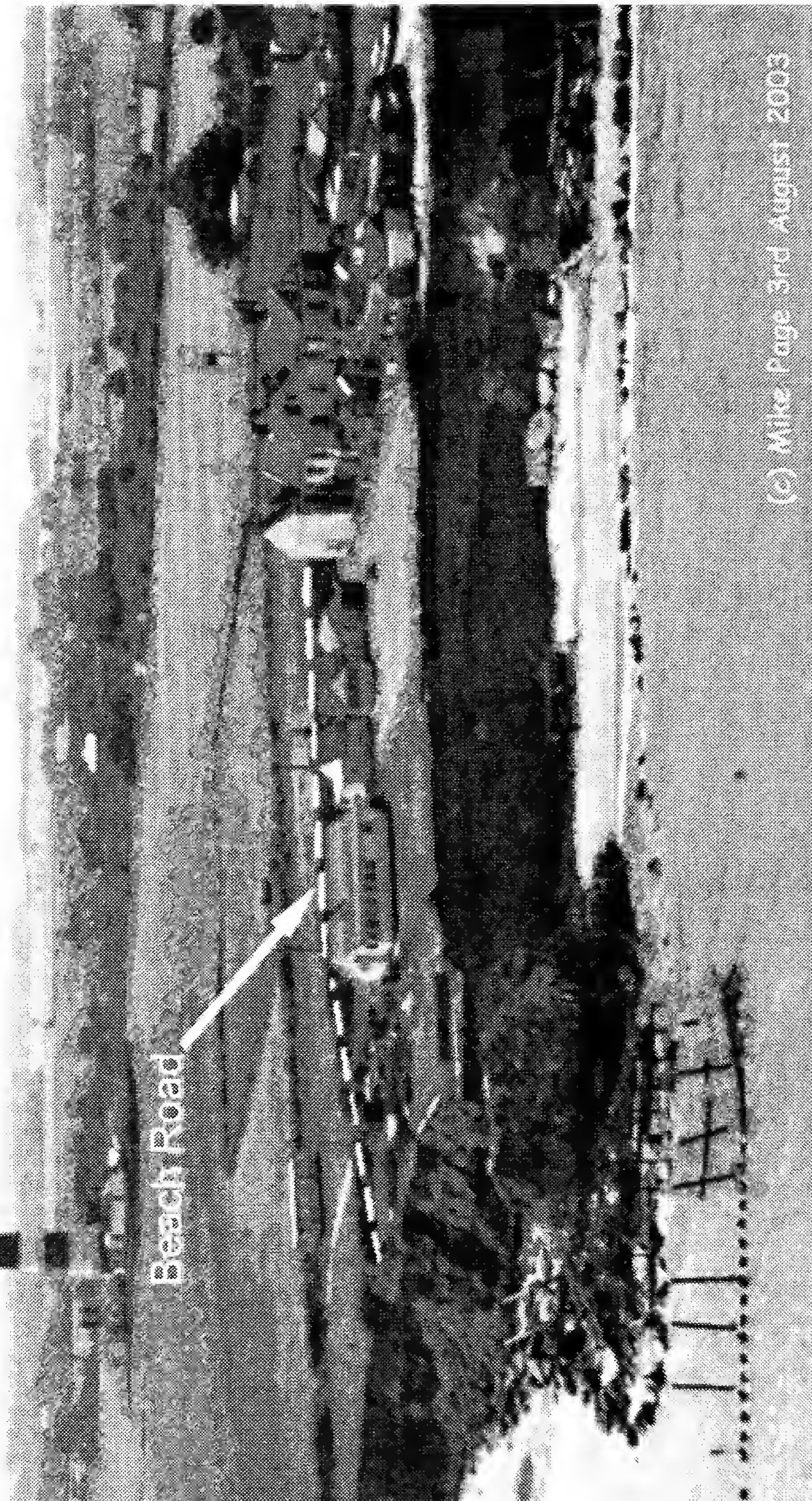


Fig. 3. Aerial view of the southern end of Happisburgh in 2003 showing the location of Beach Road, facing southwest. Photograph courtesy Mike Page, Skyview.

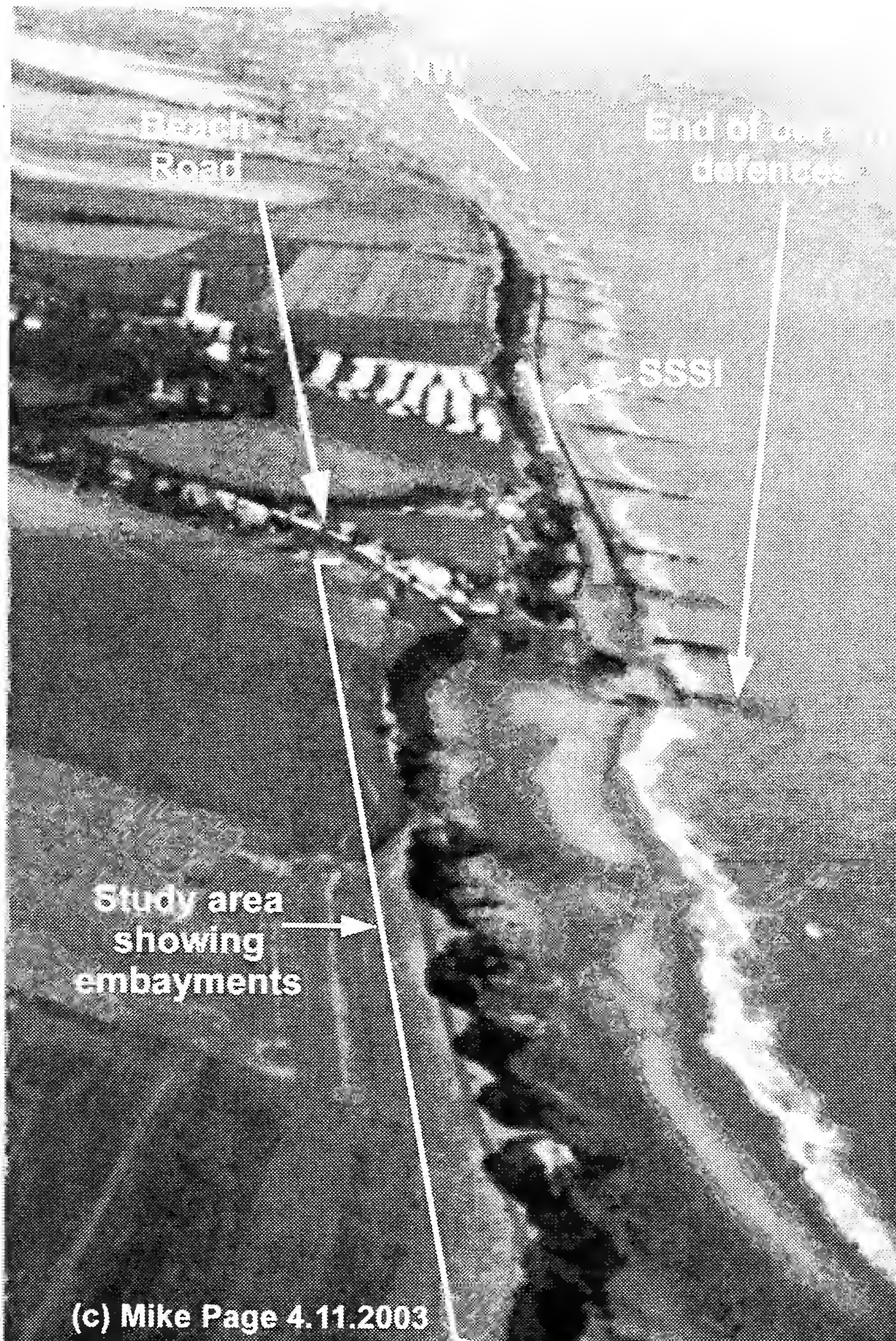
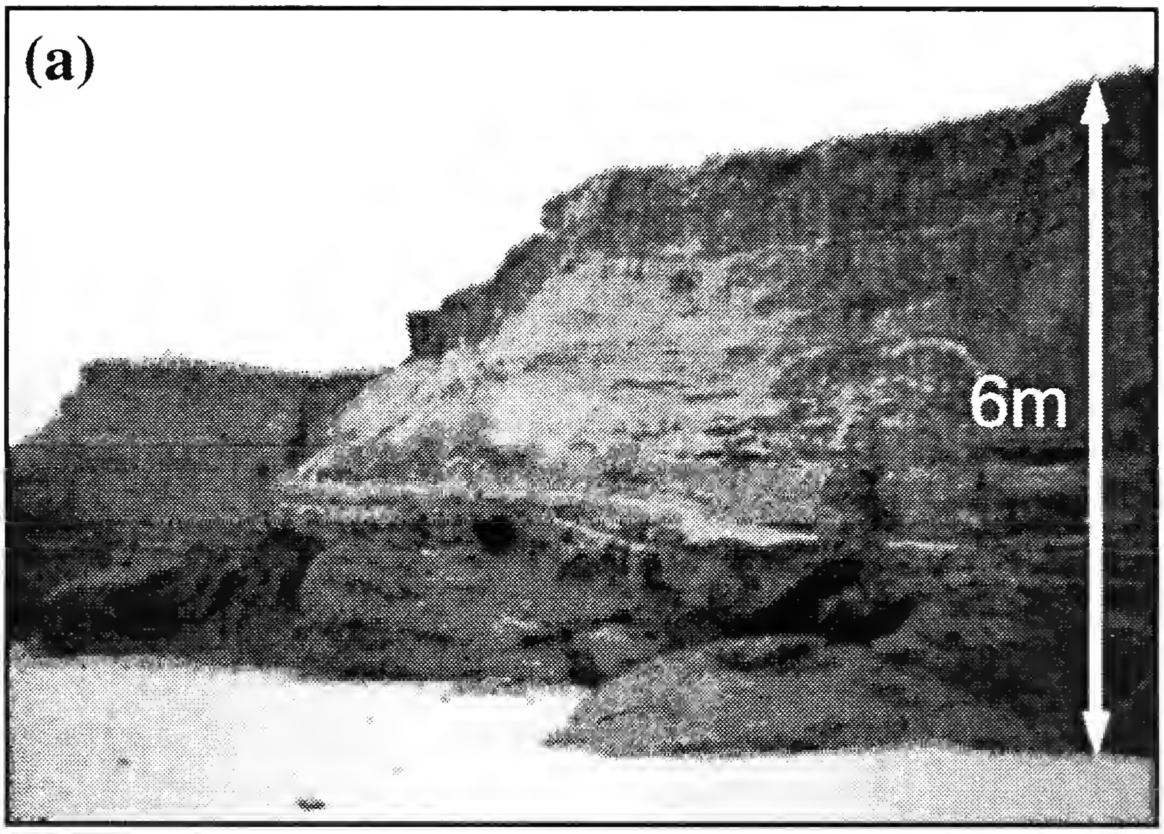


Fig. 4. Aerial photograph at Happisburgh taken in 2003, facing north, showing the point where the sea defences have failed and been removed. This sea defence line was once continuous. Also marked is the "Happisburgh Cliffs SSSI" and the study area. Photograph courtesy of Mike Page, Skyview.



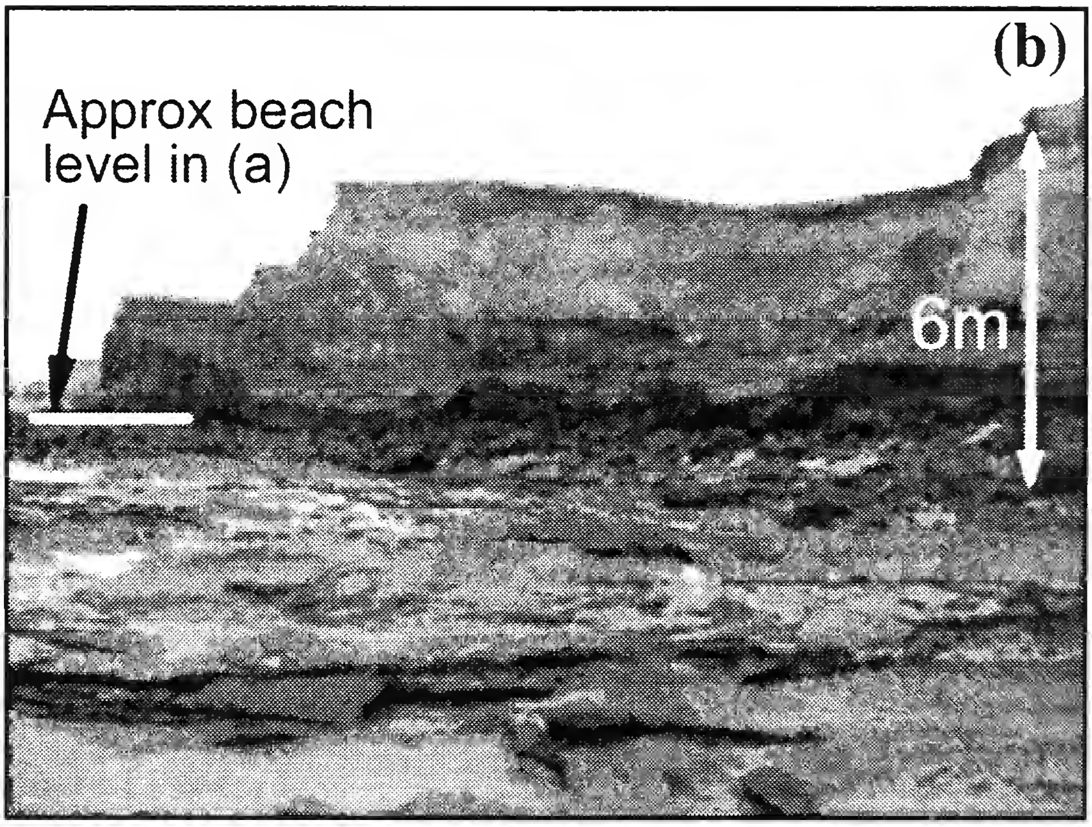


Fig. 5. (a) Cliffs at Happisburgh in September 2003. P. Hobbs © NERC. (b) Cliffs at Happisburgh after a storm event in December 2003 illustrating the drop in beach level and exposure of the Wroxham Crag Formation and the lower horizons of the Happisburgh Till. Beach lowering can also expose the Wroxham Crag (see also Fig. 9). J. R. Lee © NERC.

COASTAL EROSION AND SEDIMENT TRANSPORT

The rate at which the Norfolk cliffs are eroding has attracted considerable research. Estimates vary from 0.30 to 0.75 m a^{-1} (a = annum or years) in North Norfolk with an average of 0.9 m a^{-1} for the entire Norfolk coast from 1880 to 1967 (Cambers, 1976; HR Wallingford, 2001, 2002; Thomalla & Vincent, 2003). The Norfolk coast has retreated landward approximately, 1 to 2 km over the past 900 years records, and records such as the Domesday Book (1086) and other historical accounts, demonstrate the presence of villages that have since been lost to the sea (Clayton, 1989).

At Happisburgh, coastal erosion has been an issue for many years. In 1845, rapid coastal retreat was recognised as a threat to St Mary's Church "having an under stratum of sand and gravel, is so continuously wasted by the agitation of the tides and storms, that it is calculated the church will be engulphed in the ocean before the close of the ensuing century, the sea having encroached upwards of 170 yards during the last sixty years" (White, 1845).

This section of coast is relatively linear and faces northeast. As a result, the coastline is exposed to a wide range of wave directions (approximately 300°N to 90°N but predominantly 0°N to 70°N) and is particularly vulnerable to storms from the north due to the virtually unlimited fetch in this direction (Ohl *et al.*, 2003; Thomalla & Vincent, 2003). Various attempts to numerically model the sediment transport regime along the Norfolk coast have shown that the largest waves arrive from approximately 030°N, the most frequent wave directions come from the northwest (330°N) and the largest winds are associated with winds from the northwest and the north; therefore, the most erosive and damaging effects are broadly controlled by the sea conditions in the north (Ohl *et al.*, 2003).

The active cliff erosive processes in the Happisburgh area involve a repeated cycle of the following three stages (based on Ohl *et al.*, 2003):

1. basal undercutting of the intact toe by wave action, leading to steepening of the cliff profile and a reduction in slope stability;
2. cliff failure, involving small-scale shallow slides;
3. deposition of debris at the base of the cliff, protecting the cliff toe;
4. removal of debris from the foreshore by wave action, leading to the onset of basal undercutting (stage 1 above).

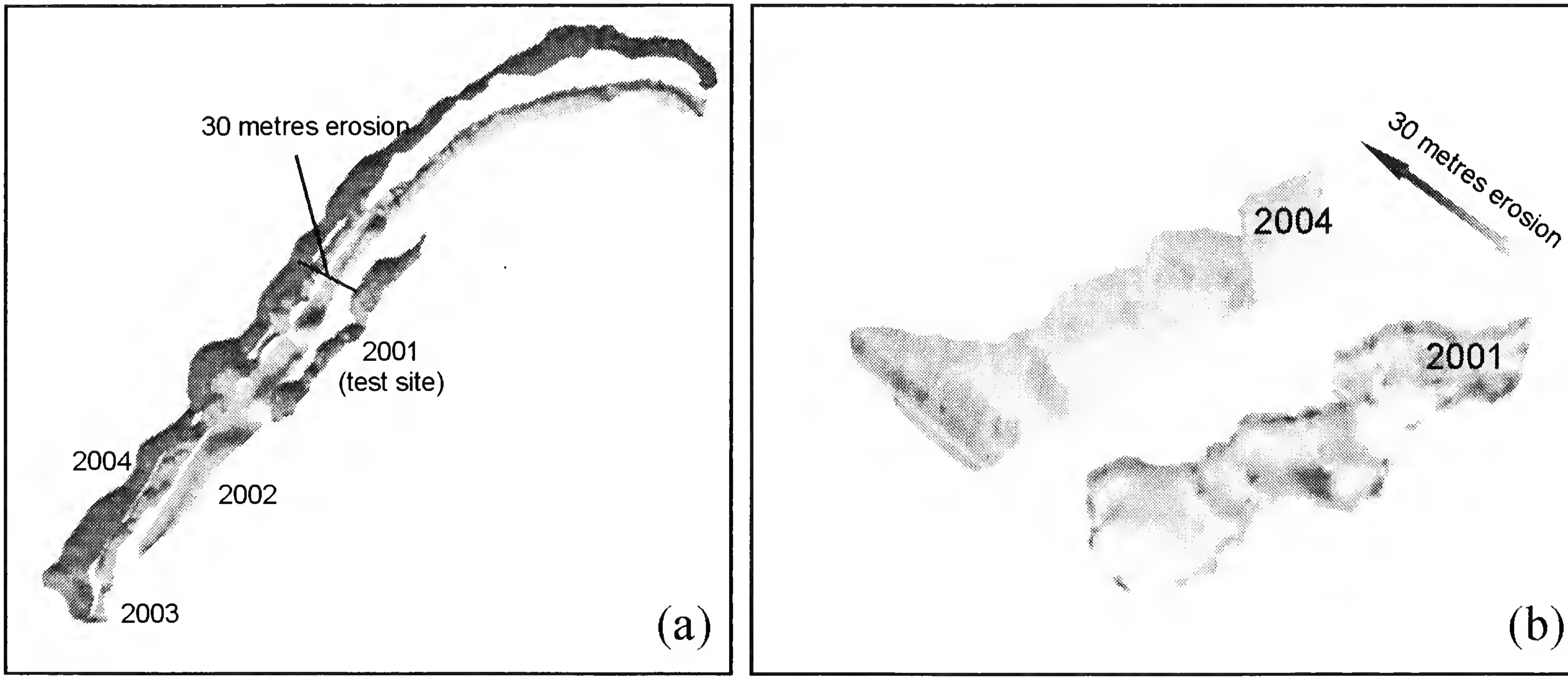


Fig. 6. (a) Four cliff surfaces as recorded by the laser. (b) Diagram showing detail of cliff scans in 2001 and 2004.

The process of mechanical erosion of the cliff face by wave action releasing cliff material has also been observed. Ohl *et al.* (2003) highlight the fact that there have been substantial short-term variations in the predicted erosion rates in response to varying weather conditions, variations in glacigenic cliff material, frequency of wave attack on the cliff base and the removal of coastal defences.

The beach levels vary significantly in this area - by up to 2 m in a single storm event (Fig. 5). A study carried out by Halcrow in 1991 identified that the cause of this was due to the oblique incidence of the waves at the coast (Thomalla & Vincent, 2003). Leggett (1993) estimated that over 140,000 m^3 of sediment was lost from the beach and more than 400,000 m^3 were lost from the near-shore area to 500 m offshore between Happisburgh and Winterton between July 1992 and March 1993 (Thomalla *et al.*, 2001).

Sediment derived from the erosion of the cliffs between Weybourne and Happisburgh is transported to the northwest and southeast along the beaches by longshore drift, with the dominant transport to the east (Cameron *et al.*, 1992). A coarsening of sand grain-size on the beaches in the direction of transport is due the removal of finer-grained sand from the beaches by wave action, followed by the transport into the nearshore zone where the sand is removed by tidal currents (McCave, 1978). Computed net annual transport rates are about 100,000 m^3yr^{-1} to the south (Clayton *et al.*, 1983).

Between Weybourne and Winterton Ness, the North Norfolk cliffs supply about 505,000 m^3 a^{-1} of sand into the littoral zone (HR Wallingford, 2001). The cliff erosion also supplies fines and gravel, the fines being transported offshore in suspension, while the sands and gravel are transported along the shore and also in the offshore area (HR Wallingford, 2002). Between Mundesley and Happisburgh the transport rate is reasonably constant to the southeast along the coastline (HR Wallingford, 2002).

At present, the rivers around the southern North Sea input very little sand. Fluvial erosion rates per unit area in East Anglia are 1–2 t km^2 a^{-1} (*t* = tonnes) (McCave, 1987); the main input is from coastal cliff erosion.

ANTHROPOGENIC EFFECTS

The construction of coastal defences along the Norfolk coast has significantly affected the rate of cliff recession. The construction and maintenance of coastal defences, mainly timber groynes and revetments, has slowed the cliff recession rates during the past few decades by trapping beach sand travelling along the coast (typically from north-west to

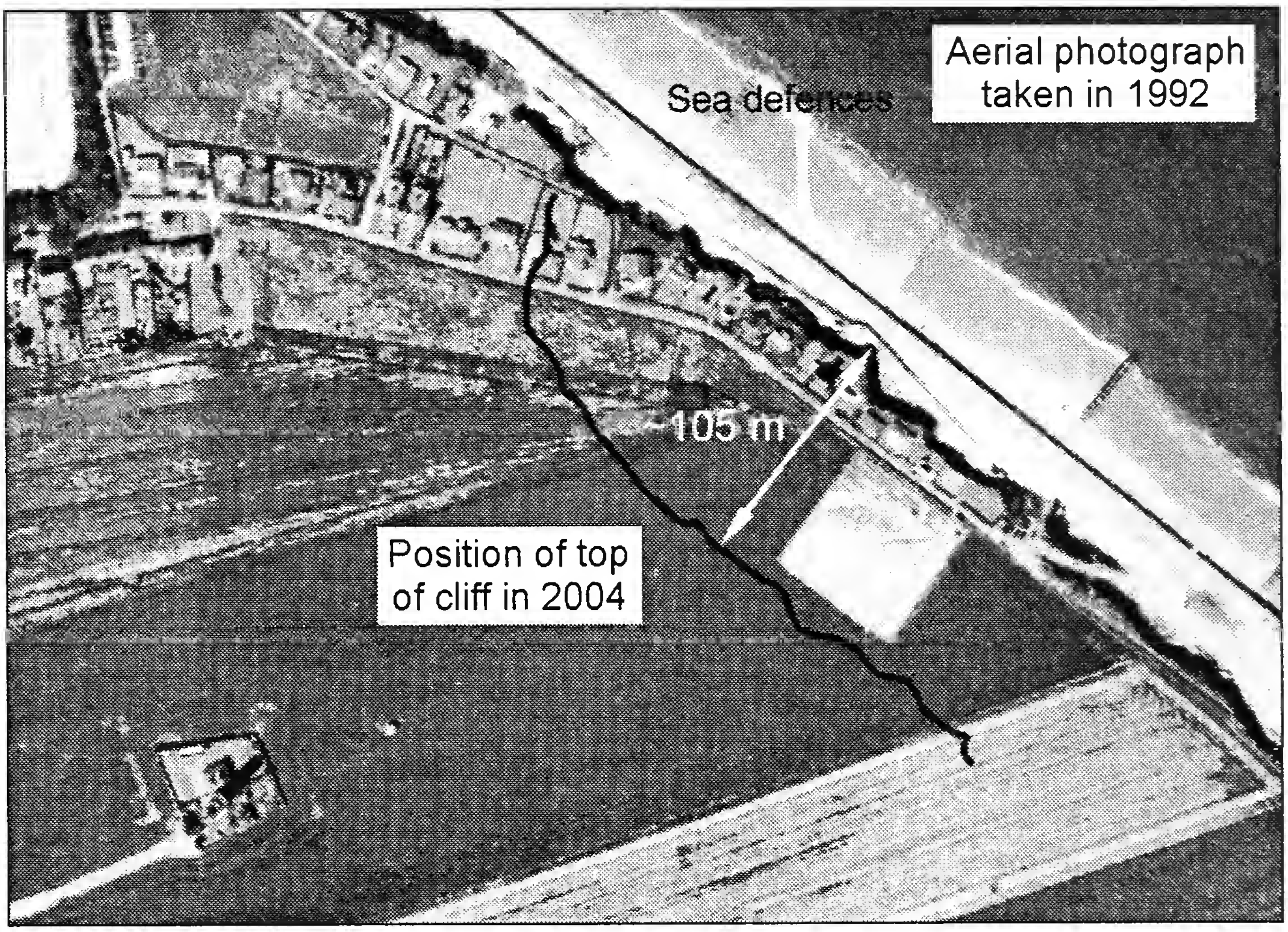


Fig. 7. A 1992 aerial photograph with line showing the location of the cliff line as measured in 2003 by BGS (photograph reproduced with kind permission of the Environment Agency, Anglian Region).

south-east) and reducing the supply of sediment arriving on the beaches down-drift of the defences (Ohl *et al.*, 2003). This has, however, caused down drift starvation and a deficit in the sediment budget at undefended sections thereby increasing the cliff recession rate (HR Wallingford, 2001).

The failure and subsequent removal of a large part of the timber palisade defences at Happisburgh in the 1990s, resulted in a 50 m cliff retreat over a 3-year period from 1996 to 1999 (Ohl *et al.*, 2003). Fig. 4 shows the point where the sea defences no longer exist at Happisburgh. It is clear from this image that the coastline has eroded significantly where it is no longer defended.

RESULTS OF THE SLOPE DYNAMICS PROJECT AT HAPPISBURGH

The rate of erosion at the Happisburgh test site has so far been monitored in 2001, 2002, 2003, 2004 and 2005 (2005 data yet to be processed) using the laser scan system. Fig. 6a and b show plots from the model illustrating the different surveys. The surveys have shown that where the defences have failed and been removed, and where the cliffs are

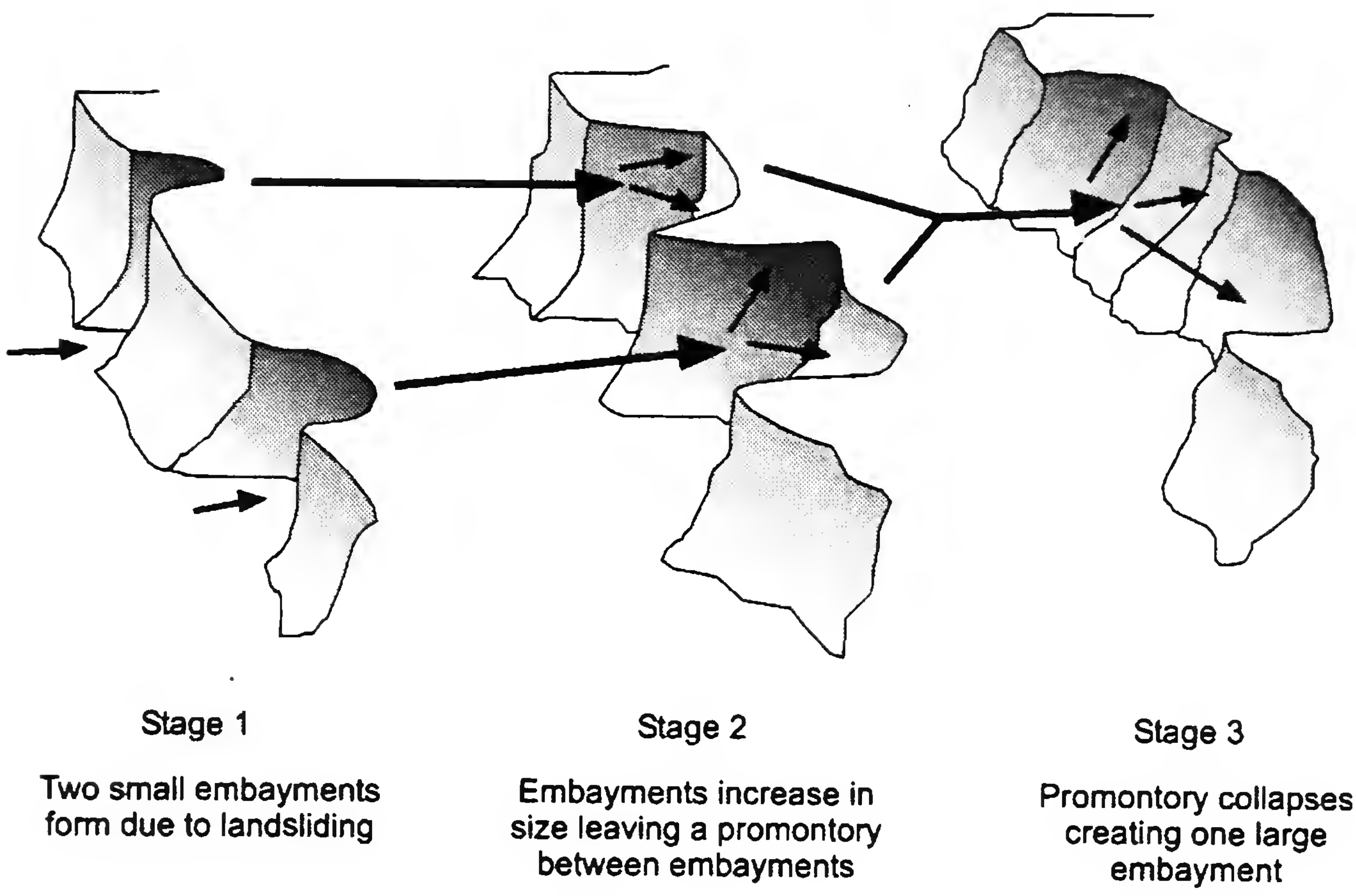


Fig. 8. Diagram to illustrate embayment formation process at Happisburgh.

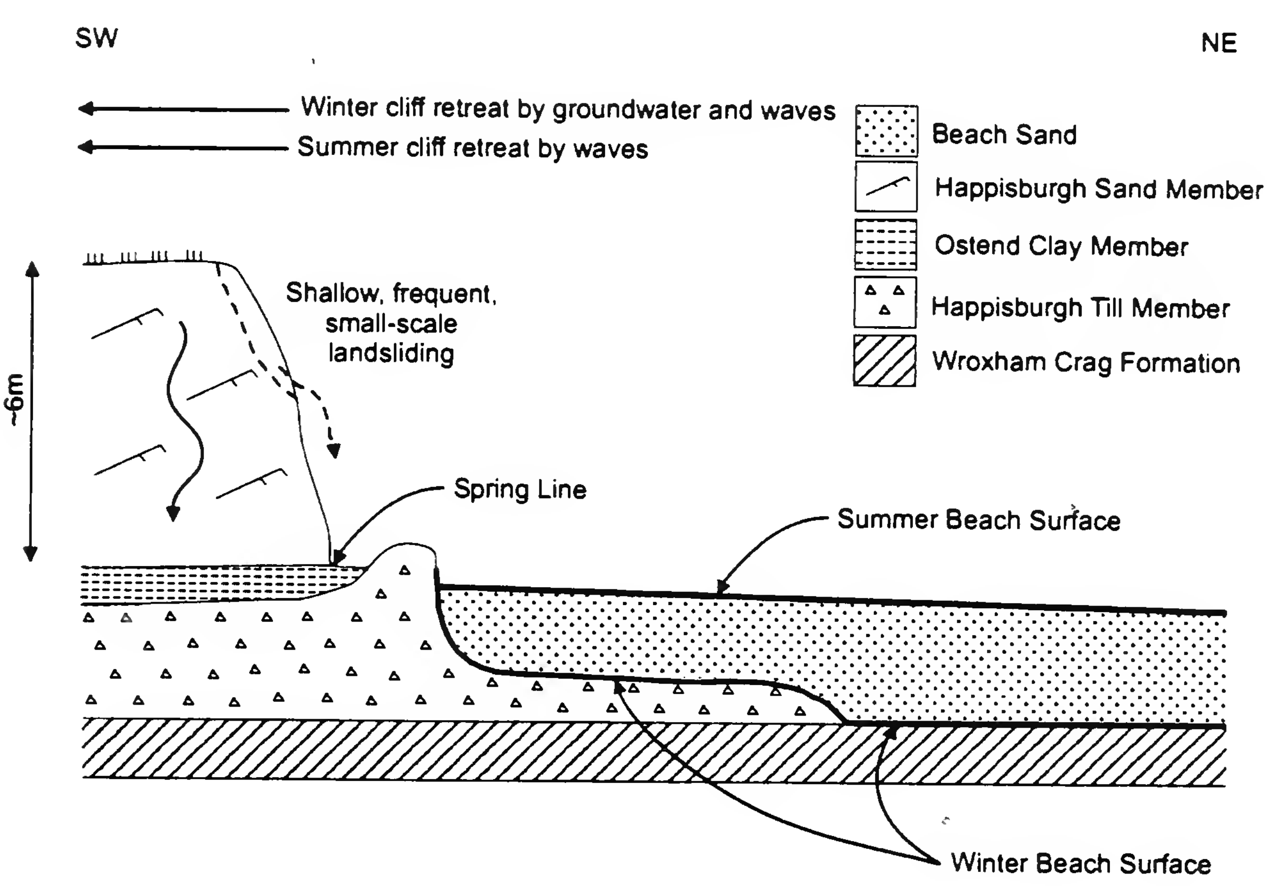


Fig. 9. Seasonal variations and erosional process model of erosion at Happisburgh

exposed (Fig. 4), erosion rates range between 8 to 10 m a^{-1}. This process has affected the properties on and adjacent to Beach Road (Fig. 3).

Early results from the surveys show that over a two-year period (September 2001 to September 2003), approximately 18,000 m^3 of sediment has been removed from a 100 m long section of cliff. This equates to approximately 36,000 t of sediment every two years.

To obtain an erosion rate over a longer time-frame, the 2004 data for the top of the cliff was drawn onto an aerial photograph from 1992 (Fig. 7). In this 12-year period the coast has retreated by approximately 105 m along a 400 m section.

The cliff surface profiles show that the erosion process is non-uniform, involving the cyclic formation of a series of embayments that continually enlarge (Fig. 4, Fig. 8). This could infer landsliding processes involving block falls, mudflows and running sand.

The aforementioned cliff recession conceptual model (Ohl *et al.*, 2003) is largely correct. However, the seasonal beach-level changes at Happisburgh have a considerable effect on the erosion and landsliding process. The following conceptual model is proposed (Fig. 9):

1. In winter, erosion caused by groundwater as seen in the gullying of the cliff face, coupled with increased seasonal storminess, causes small-scale, frequent, shallow landsliding in the Happisburgh Sand Member. The Happisburgh Sand Member is easily eroded and undercutting of the cliff toe reduces slope stability and cliff failure occurs. The beach surface is low and scouring of the upper surface of the till extends the till platform.
2. In summer, the beach surface is higher and covers the 'winter platform'. Wave attack is the dominant form of erosion accompanied by landsliding in the Happisburgh Sands.

CONCLUSION

The surveying method described is believed to be a highly accurate method to model not only rates of coastal retreat, but also detailed surface profiles of the cliff face. It enables an accurate analysis and interpretation of different failure types and mechanisms of failure and geological cross sectional mapping of the cliff face.

Detailed knowledge of the quantities of sediment input to the budget from cliff erosion has been very difficult to measure in the past. This method enables calculation of

overall volume changes providing useful information for beach profiling and sediment budget studies as well as sea defence design and maintenance.

Several authors have attempted to model coastal retreat using Ordnance Survey (OS) maps but have recognised surveying errors of up to 1 m or more (Hooke & Kain, 1982; Nicholls & Webber, 1987; Gray, 1988; Cosgrove *et al.*, 1998). Aerial photogrammetry, while more accurate than interpreting topographic maps, relies on accurate ground control that is not always available in such a dynamic environment. This method calibrates models and measurements made.

The advantages and benefits of terrestrial laser scanning in the coastal environment are: (1) rapid data collecting technique enabling detailed cliff surface profiles to be captured in a matter of hours such that tides are not a problem; (2) responsive methodology allowing, for example, landslide events to be scanned as soon as the team get on the site; (3) inexpensive after initial equipment purchase; (4) data requires less post-fieldwork processing than terrestrial photogrammetry; (5) 3-D cliff face surface models can be built up over time and volume loss calculations are easily and accurately obtained; (6) when used in conjunction with sub centimetre capability GPS promotes excellent spatial positional accuracy of the scans. Also, access to the cliff is not necessary as with some other survey methods.

At the beginning of 2005, BGS purchased a new laser capable of greater accuracy and resolution and the 2005 scan data is currently being processed.

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MIDDLE PLEISTOCENE GLACIAL AND GLACIOFLUVIAL SEDIMENTS AT BURGH CASTLE, NORFOLK: SEDIMENTOLOGY, STRATIGRAPHY AND IMPLICATIONS FOR NEOTECTONICS

Riches, P.F.[1], Rose, J.[1], Lee, J.R.[2], & Palmer, A.P.[1]*

[1]Department of Geography, Royal Holloway, University of London,
Egham Surrey, TW20 0EX.
[2]British Geological Survey, Keyworth, Nottingham, NG12 5GG.
* email: p.f.riches@rhul.ac.uk

ABSTRACT

Quaternary sediments in Welcome Pit near Burgh Castle (Norfolk) are described and the processes that deposited and deformed the sediments are interpreted. A lithostratigraphy is proposed and the results are used to test; 1) whether the region was glaciated by more ice sheet expansions than a single glaciation in Marine Isotope Stage (MIS) 12; 2) whether there is evidence for glaciation in the early Middle Pleistocene, the period known as the Cromerian Complex, and 3) whether the region been affected by neotectonic processes in the interval since the early Middle Pleistocene?

Sands with gravel are interpreted as part of an outwash plain formed near the southern limit of the British, Happisburgh Ice Sheet. These sediments have been overridden and deformed by the ice on several occasions during which thin till units were deposited between thinly bedded outwash sediments. The final withdrawal of the Happisburgh Ice Sheet from the area is marked by the deposition of higher energy, thicker and laterally extensive outwash sands and gravels. Subsequently the Anglian Ice Sheet (MIS 12) advanced across the area and deposited subglacial till. There are indications that the later stages of the Happisburgh Glaciation meltwater drainage may have been influenced by a NE-SW structural grain visible in the underlying Crag.

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INTRODUCTION

Considerable attention has recently been given to the nature of climate and environmental change during the early Middle Pleistocene (c. 780 – 450 ka BP) due to the recognition that this period provides the first evidence for high magnitude climate change following the mid-Pleistocene transition (Roy *et al.*, 2004), and because of conflicting evidence about the scales of these changes as shown in ice cores (EPICA community members, 2004) and in the oceans (Shackleton *et al.*, 1990; Bassinot *et al.*, 1994). In NW Europe the nature of these changes is expressed in the changes of physical systems over the land areas and within the adjacent shallow seas. Interpretation of this evidence has resulted in a number of debates, including the timing and extent of lowland glaciation during the Middle Pleistocene (Mangerud *et al.*, 1996; Hamblin *et al.*, 2000; Banham *et al.*, 2001; Lee *et al.*, 2004a, Clark *et al.*, 2004), the frequency and magnitude of temperate episodes with high sea-level and dense temperate forest vegetation (Preece and Parfitt, 2000), and the possibility that neotectonic uplift or subsidence may play a significant role in landscape development as a consequence of the operation of surface processes (Maddy *et al.*, 2000, Rose *et al.*, 2002, Westaway *et al*, 2002;).

East Anglian geology has played a critical role in understanding the Pleistocene palaeoenvironmental history of NW Europe with major new discoveries of complex marine, fluviatile and glacial stratigraphies and the recognition of palaeosols formed in a range of climates (Rose *et al.*, 1999b, 2000a,b, Candy, 2002; Lee *et al.*, 2004a,b, 2006). The reason for this region having such an important role is its position at the western margin of the North Sea basin and its association with moderate sized rivers which transported substantial quantities of sediment to both their lowland reaches and coastal regions, providing an archive of environmental records. This circumstance is enhanced because, for reasons not yet understood, glaciers extended into the region without effecting significant erosion, and in many places these glaciers simply buried existing sediments and landscape and thus preserved critical evidence for future study (Rose *et al.* 1985). The result is that four groups of sediments are developed in NE East Anglia and these deposits provide evidence by which it is possible to test the models for climate and environmental change during the early Middle Pleistocene.

The oldest unit is the Norwich Crag Formation, which is a shallow marine deposit that forms the lower parts of the succession and exists at depth in basins that extend below

present sea-level (Fig. 1). Above this, the Wroxham Crag Formation represents shallow marine sediments (estuarine and offshore sands, gravels and muds) that extend across much of the region (Fig. 1; West, 1980, Preece and Parfitt, 2000, Rose *et al.,* 2001). The Cromer Forest-bed Formation outcrops along the coast between Sheringham in the NW and Kessingland in the SE and locally inland, and represents terrestrial materials and landforms deposited by the Ancaster and Bytham rivers (Fig. 1) that fill channels cut into the Wroxham Crag. The fourth unit is the tills that cover much of the same region. These consist of a lower sandy till, a middle chalky, clay-rich till and an upper sandy till (Lee *et al.,* 2004b).

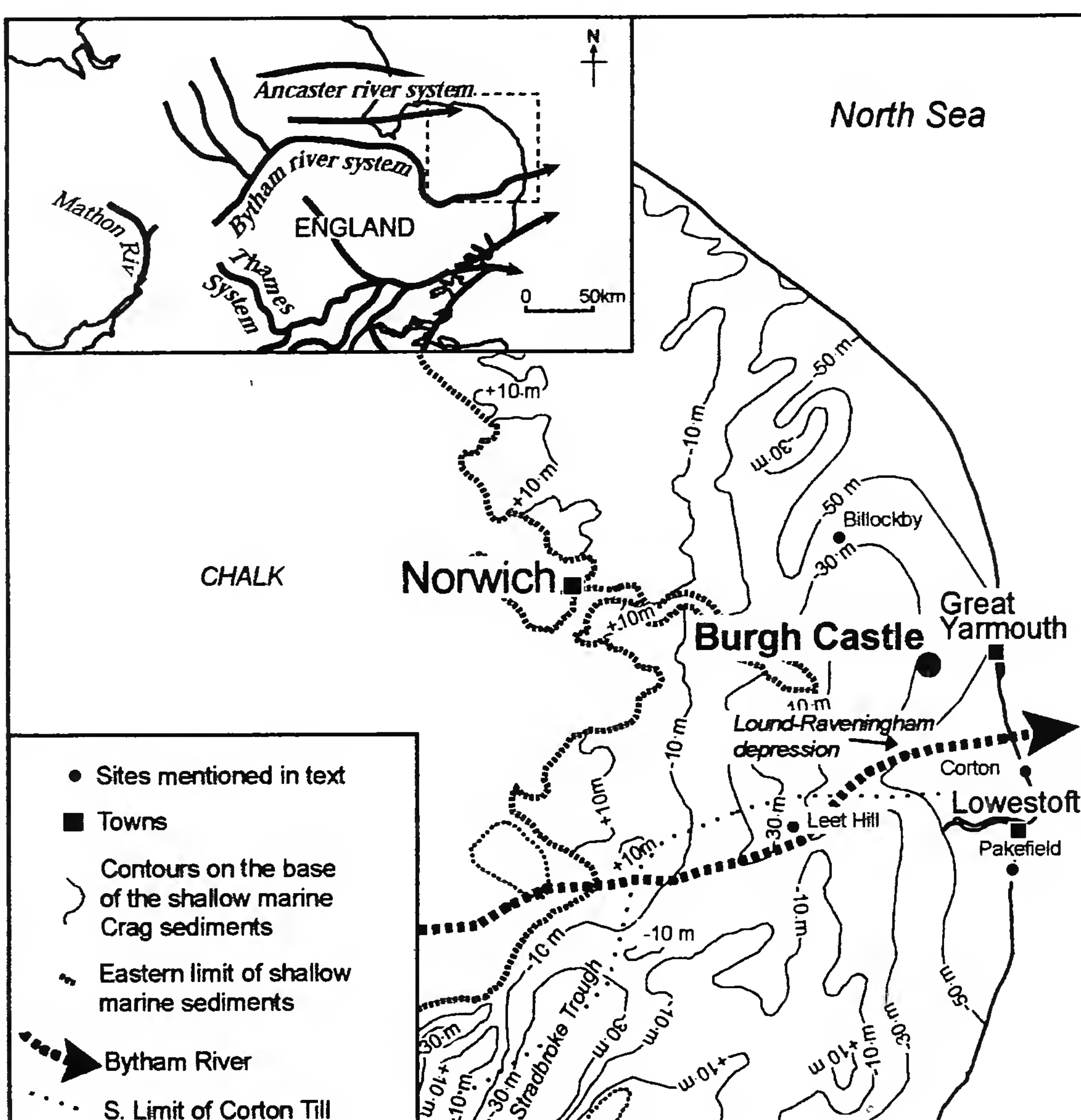

Fig. 1. Location maps showing extent of marine sediments (Crag) and structure on the base of the Crag (from Zalasiewicz *et al.,* 1988), course of ancestral Bytham River (from Rose *et al.,* 2001) and a preliminary S limit of the Corton Till (and its equivalent Starston Till). Upper inset shows regional river pattern prior to the Anglian Glaciation (MIS 12).

Traditionally these tills, originally known as the North Sea Drift (the sandy tills) and the Lowestoft/ Walcott Tills (the chalky clay till) (Perrin *et al.,* 1979) had been separated from the Wroxham Crag and Cromer Forest-bed formations and ascribed to a single ice-sheet expansion attributed to the Anglian (Marine Isotope Stage 12) (Bowen *et al.*, 1986). Typically all deposits below the tills (the Cromer Forest-bed and Wroxham Crag formations) were known as pre-glacial (cf. West, 1980). However, since 2000 the glacial deposits have, on the basis of new observations, been attributed to three separate ice sheet expansions and allocated to three separate marine oxygen isotope stages: MIS 16, 12 and 10 (Hamblin *et al.*, 2000, 2005; Rose, 2000; Lee 2003, Lee *et al.*, 2004a). Despite the record of new discoveries in the form of lithostratigraphic properties (continuity of sedimentary units, changing heavy mineral and clast signatures, correlation with climate-forced river sediment sequences), much scepticism still remains about issues such as the case for glaciations before MIS 12, and the existence of more than one glaciation around this time (Banham *et al.*, 2001; Whiteman, 2002).

Clearly, the ability to test the various hypotheses and contribute to understanding the nature of climate and environmental change during the early Middle Pleistocene depends on the quality of the exposures of the fragmented deposits within the area. Welcome Pit at Burgh Castle (Fig.1, National Grid Reference TG 484 044), near Great Yarmouth in east Norfolk currently shows a sequence of sands and gravels and diamictons that contribute to this research (Fig. 2). This site has been described briefly by Westgate (1965), Ranson (1968), Hopson & Bridge (1987), Arthurton *et al.* (1994), and was studied in some detail by Bridge & Hopson (1988). However, these studies occurred before the character of the climate and environment of the Middle Pleistocene was known from marine and ice cores (Bassinot *et al.*, 1994, EPICA Community Members, 2004; Bitanja *et al.*, 2005). Current exposures allow us to address three research themes: 1) was the region glaciated by more ice sheet expansions than a single glaciation in MIS 12; 2) is there evidence for glaciation in the early Middle Pleistocene, the period known as the Cromerian Complex; 3) has the region been affected by neotectonic processes in the interval since the early Middle Pleistocene?

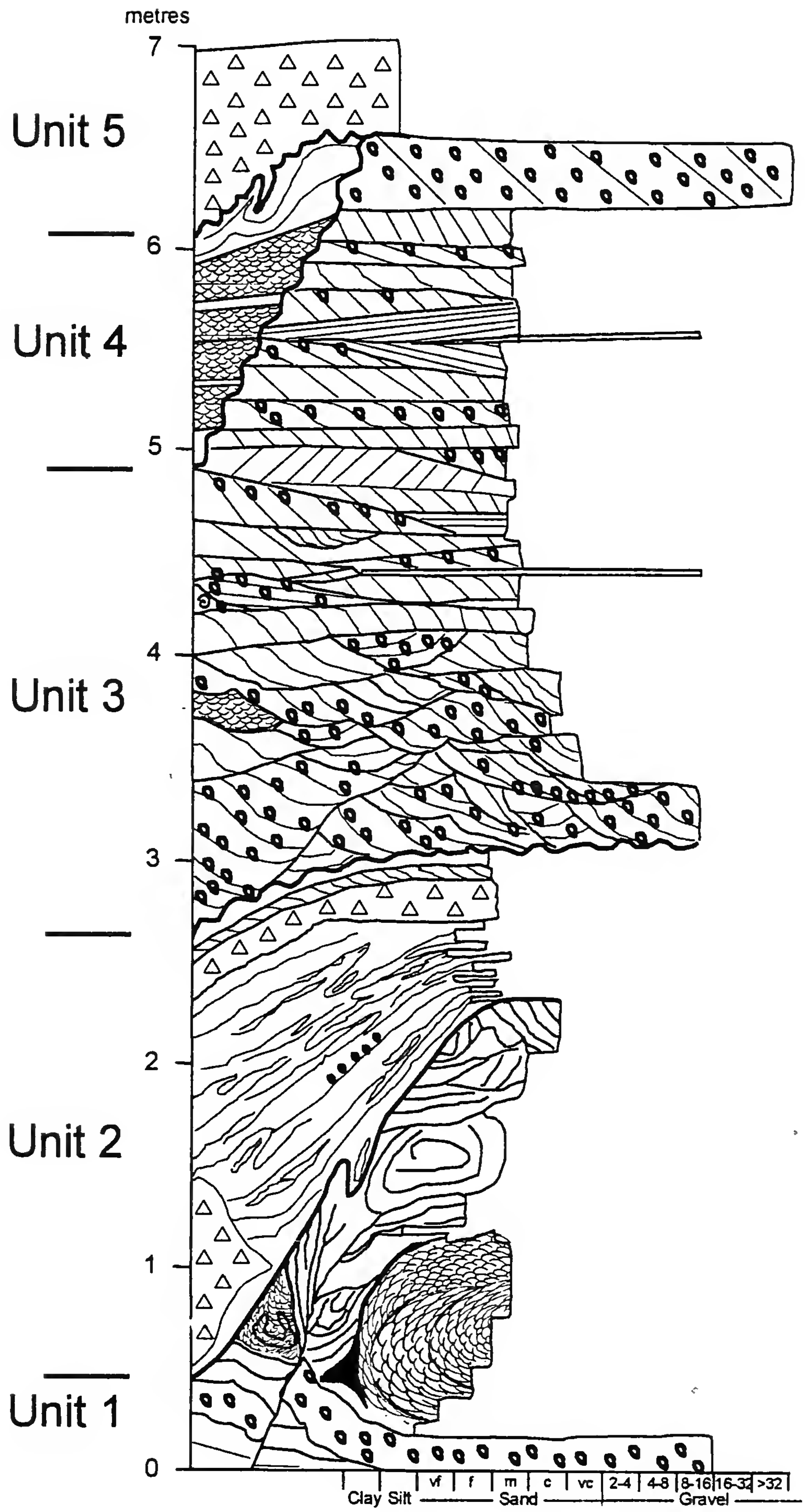

Fig. 2. Composite stratigraphic section of exposures in Welcome Pit, Burgh Castle. Total variation in unit thickness not shown. See text for detailed descriptions.

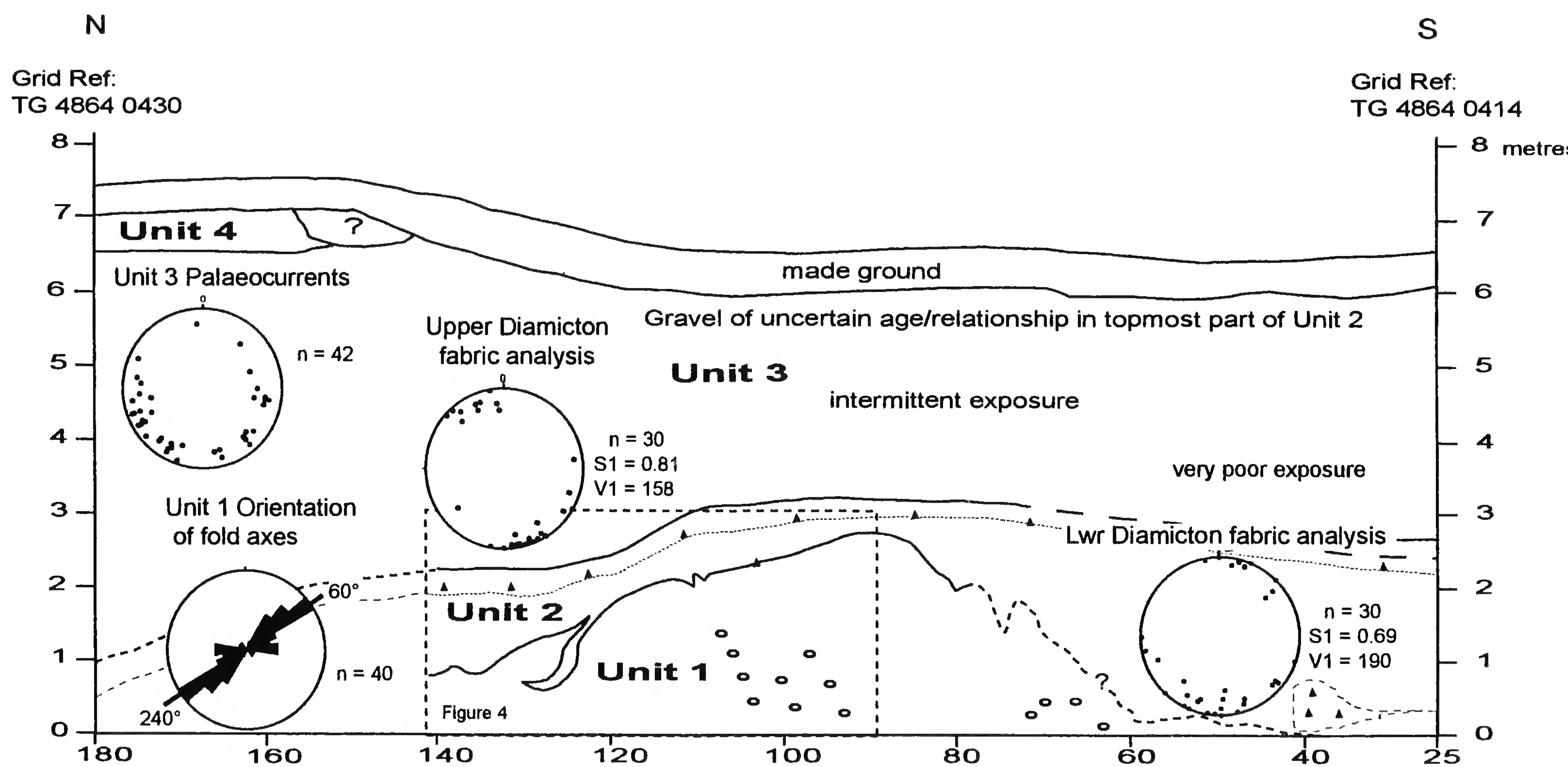

Fig. 3a. Eastern face of Welcome Pit, Burgh Castle. Small circles represent deformed gravel horizons within Unit 1. Dotted outline shows position of Fig. 4. Elevation of base of section is approximately 3 m OD.

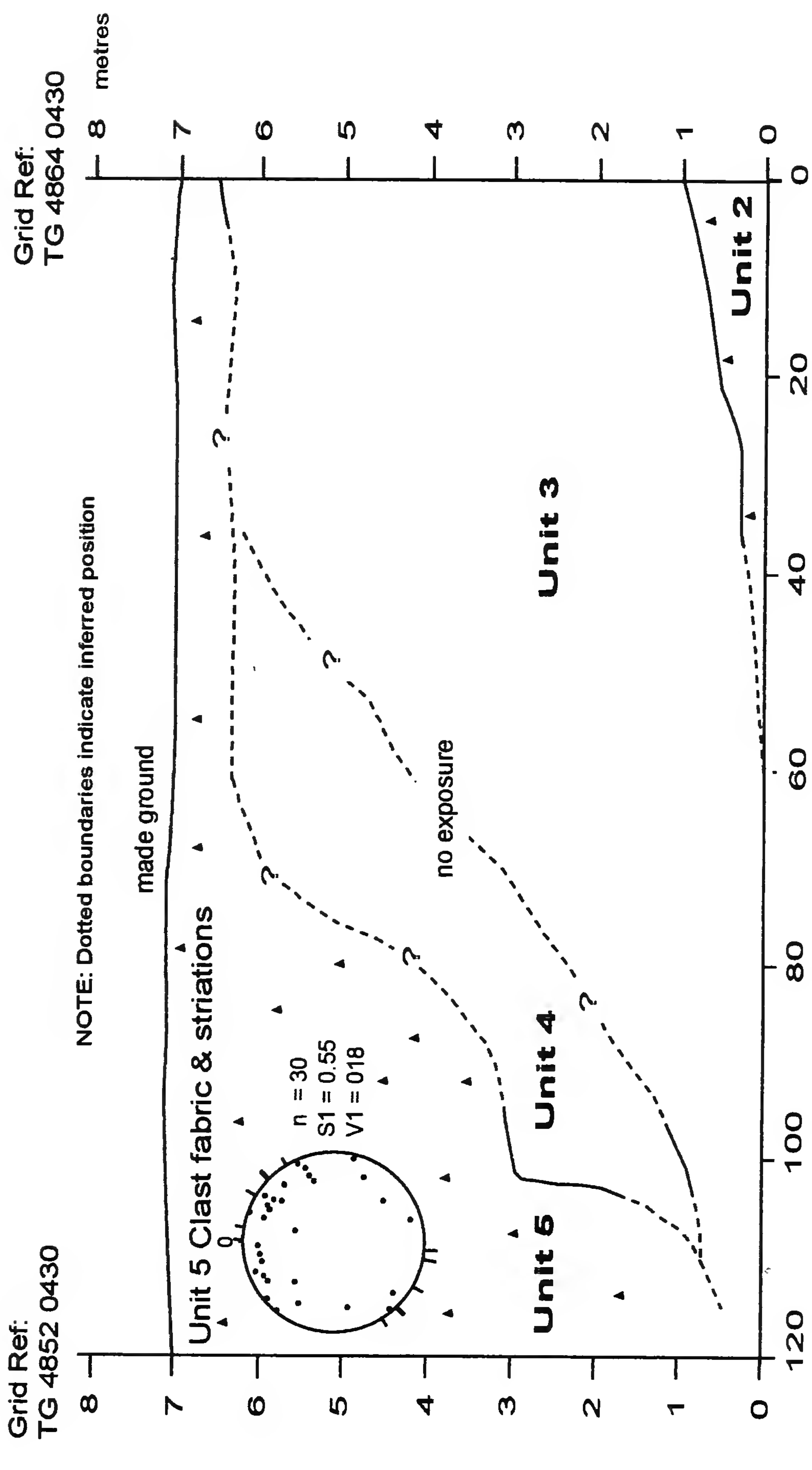

Fig. 3b. Part of northern face of Welcome Pit, Burgh Castle.

Elevation of base is approximately 3 m O.D.

LOCATION AND LOCAL GEOLOGY

Welcome Pit at Burgh Castle is located 6 km WSW of the centre of Great Yarmouth. The site is on an 'island' of Pleistocene sediments that are surrounded by the sea to the east and the Holocene river and marine muds to the north, west and south. The 1:50,000 scale geology map of the area (Great Yarmouth, Sheet 162) shows Corton (now Happisburgh) Formation (sand, sandy clay and gravel) locally overlain by Lowestoft Formation (chalky sandy clay). The local land surface elevation ~ 10 m OD.

METHODOLOGY

Detailed section logging of selected accessible parts of the actively worked eastern face and small exposures in the northern face were conducted to understand the lateral and vertical variations in facies and structure (Fig. 3a, b). To aid interpretation of the deformed sediments in the lower part of the eastern section a 50 m length (Fig. 4) was exposed with a mechanical digger and described in detail. All structures, sediments and sample locations were recorded on a spatial grid for accuracy. The colour of sediments was determined using Munsell Color Charts. The calcium carbonate content of sediments was determined using an Eijelkamp 08.53 Calcimeter and the gasometric method (Gale and Hoare, 1991). Structural measurements, palaeocurrent directions and clast fabric patterns were determined.

Representative bulk samples of different lithologies were collected for laboratory analyses. Samples of diamictons were collected in Kubiena tins from which thin sections were prepared, using the acetone replacement method (Carr & Lee, 1998), for micromorphological investigation (van der Meer, 1993). Dry sieving (Gale and Hoare, 1991) was used to determine the particle size distribution of the >63 μm fraction and the fraction <63 μm was analysed using a Micrometrics Sedigraph 5100 (Coakley and Syvitsky, 1991). The calcium carbonate content of sediments was determined by the gasometric method (Gale and Hoare, 1991) using an Eijelkamp 08.53 Calcimeter.

Heavy mineral analysis (Gale and Hoare, 1991) was carried out on selected samples of the 63 – 125 μm sand fraction, with a minimum grain count of 500 grains. This size range was chosen to reduce the effects of hydraulic sorting and to enable comparison with other studies in the region (Perrin *et al.*, 1979; Bridge & Hopson, 1985; Lee *et al.*, 2004a,b, 2006). Clast lithology analysis (Bridgland, 1986) of the 8-16mm and 16-32mm gravel

Table 1. Some of the lithostratigraphic units for early Middle Pleistocene in E Norfolk (from Bowen, 1999; Lee *et al.*, 2004; Rose *et al.*, 2001). Units referred to in this paper in bold type. Oldest units are at the base, but no stratigraphic equivalence is implied horizontally across the table.

Bytham River (fluvial)	**Wroxham Crag (marine)**	**Happisburgh Formation (glacial & glaciofluvial)**
Castle Bytham Terrace Mb.	Mundesley Mb.	**Corton Sand Mb.**
Warren Hill Terrace Mb.	How Hill Mb.	**Leet Hill Sand & Gravel Mb.**
High Lodge Mb.	Dobb's Plantation Mb.	**Corton Till Mb.**
Timworth Terrace Mb.		Happisburgh Sand Mb.
Knettishall Terrace Mb.		Ostend Clay Mb.
Ingham Terrace Mb.		Happisburgh Till Mb.
Severn Hills Terrace Mb.		

Mb. = Member

fractions was carried out, emphasizing the 8-16mm size range because of the ability to obtain larger sample sizes.

The lithostratigraphic frameworks of Lee *et al.* (2004a, b) and Rose *et al.* (2001) are used in this paper (Table 1).

DESCRIPTION OF THE SECTION

Five sedimentary units (Fig. 2) were identified; units 1, 2, 3 and 5 are exposed in the eastern quarry face (Fig. 3a). Unit 5 is confined to the northern end of the quarry while Unit 4 is only visible in part of the poorly exposed northern face (Fig. 3b).

Unit 1

This unit is composed predominantly of non-calcareous sands with occasional sands with gravels and thin beds and laminae of mud. Unit 1 is 2.8 metres thick in the middle of the eastern face but the base is not exposed.

The sands of Unit 1 are very pale brown (10YR 7/4) to brownish yellow (10YR 6/8) and mainly very fine to medium grained. Coarse sands are present locally. The sand fraction is moderately well sorted and clay content increases from less than 5% in the coarser sands (BC33, 37, Table 2) to 15% in the very finest sands (BC30, Table 2). Type A ripple bedding (Jopling and Walker, 1968) is widely developed in very fine to medium grained sand, generally in upward coarsening sequences. The upward coarsening sequences

Table 2. Particle size analysis of representative sediments in Units 1-5, Welcome Pit Burgh Castle.

		Clay (%)	Silt (%)	Sand (%)					Gravel (%)	Gravel mode
				v. fine	fine	medium	coarse	v. coarse		
Unit 5	BC950	42	23	18	3	1	0	0	13	*32-64mm*
Unit 4	BC310	6	5	16	51	17	4	1	0	
	BC308	26	58	11	4	1	0	0	0	
	BC307	7	12	55	26	<1	0	0	0	
	BC304	10	7	43	39	1	0	0	0	
Unit 3	*BC73*	*<1*	*<1*	*3*	*10*	*16*	*8*	*2*	*60*	*32-64mm*
	BC19	1	0	1	25	59	13	<1	0	
	BC71	*<1*	*<1*	*3*	*17*	*33*	*20*	*4*	*23*	*8-16mm*
	BC23	1	0	1	24	50	20	4	0	
	BC72	*<1*	*<1*	*1*	*11*	*37*	*22*	*4*	*24*	*8-16mm*
	BC22	1	0	1	7	53	35	3	0	
									0	
Unit 2	BC78	23	16	20	17	11	4	1	8	*none*
	BC43	6	4	14	68	7	1	0	0	
	BC8	3	1	3	42	49	2	0	0	
	BC 4	14	7	49	23	7	0	0	0	
Unit 1	BC63	33	40	15	9	3	0	0	0	
	BC37	5	2	2	17	38	32	4	0	
	BC33	3	1	2	35	52	5	<1	0	
	BC30	15	7	67	10	0	0	0	0	
	BC74	*<1*	*<1*	*1*	*10*	*28*	*17*	*5*	*38*	*8-16mm*

commence with beds of uniform grain-size that pass abruptly upwards into successive beds of increasing grain size. The boundaries between the beds can be either erosional or conformable and bed thickness (~10 to 40 cm thick) tends to increase with grain size. Horizontal planar bedded fine to coarse grained sands and cross bedded medium to coarse sands also occur. Cross bedded sands occur at the top of the unit and foresets occasionally have silty clay drapes. Small clay platelets with angular edges occur sporadically in ripple bedded, fine to medium sands. Diagenetic iron and manganese nodules up to 3 centimetres in length occur locally within coarse grained sands. The original depositional relationships of the beds within the Unit have usually been destroyed by post depositional deformation. The cross bedded units are usually too deformed to determine reliable palaeocurrent directions but, where measurements can be made, flow directions appear to be to the W and to the SE. Heavy mineral assemblages in the sands (BC1, BC30 in Table 3) are dominated by opaques (71-83%). In the non-opaque fraction, epidote (26-44%) and amphibole (16-22%) are dominant with zircon, garnet and tourmaline each reaching between 5 and 17% of the non-opaques.

The sands with gravels occur in the lower part of the unit and the depositional relationships of the beds have been obscured by subsequent deformation and poor exposure. Apparent bed thicknesses vary from 10-55 cm and trough and planar cross bedding is visible locally. The size distribution of the sand and gravel beds is bimodal (BC74 Table 2) and can be either matrix or clast supported. The sand is medium grained, poorly sorted, pale brown

Table 3. Heavy mineral analyses of very fine sand fractions (63-125 μm) from different, lithostratigraphic units at Burgh Castle. Totals may not equal 100% owing to rounding.

				Percent of non-opaque fraction										
UNIT	Sample	Total grains	**Percent opaques**	**epidote**	**amphibole**	**zircon**	**garnet**	**tourmaline**	**apatite**	**rutile**	**kyanite**	**pyroxene**	**staurolite**	**other**
4	BC308	503	66	36	30	6	7	3	10	1	0	2	0	5
3	BC19	*524*	42	28	26	10	28	1	1	1	1	0	0	3
3	BC23	*546*	31	22	22	15	29	2	2	2	1	1	1	3
2	BC13	*517*	36	33	26	14	5	7	2	3	2	3	1	5
2	BC4	*514*	62	46	12	10	7	12	2	2	2	1	1	4
1	BC30	*514*	71	44	16	10	5	12	5	1	1	1	1	5
1	BC1	*627*	83	26	22	17	11	10	3	5	0	1	1	4
1	BC74	*867*	86	29	23	14	13	9	3	2	1	1	2	4

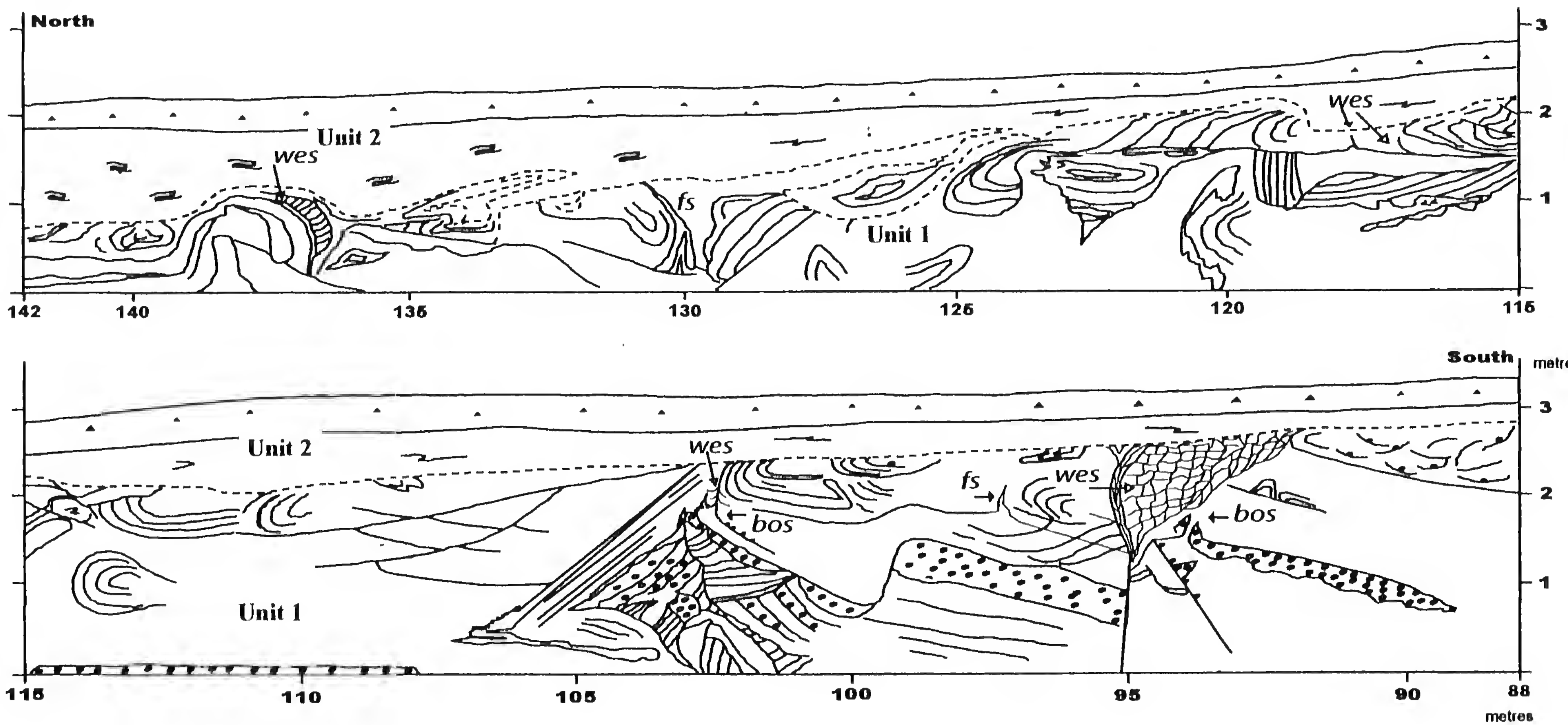

Fig. 4. Lower part of the section from 88 – 142 m in the east face of Welcome Pit, Burgh Castle showing the deformational style in Unit 1 including folding, thrusting, faulting, water escape structures (wes), "burst out" structures (bos) and flame structures (fs). The Unit 1/ Unit 2 boundary shown as dashed line. Horizontal metre markers correspond to those in Fig. 3a.

(10YR 7/4). The gravels are matrix and grain supported and composed of up to 40% pebbles (mode 8-16 mm) which are also poorly sorted. The gravel clasts (BC74, Table 4) are composed predominantly of flints (79%), mainly brown, and quartzose material (16%). Quartzose material is predominantly white, vein quartz (10%) and quartzites (4%) with red and brown quartz and quartzites reaching 2%. Greensand, Carboniferous and *Rhaxella* cherts are present and each represent less than 1% of the clasts. Identifiable far travelled igneous and metamorphic erratics make up 1.1% of the clasts and are derived from a northern source (Lee *et al.,* 2002). The heavy mineral assemblage (BC74, Table 3) is characterised by a very high opaque mineral concentration (86%) and non-opaques are dominated by epidote (29%) and amphibole (23%) with significant zircon (14%), garnet (13%) and tourmaline (9%).

The beds of poorly sorted mud (BC63, Table 2) are brownish yellow (10YR 6/6) to yellowish brown (10YR 5/8). Beds range in thickness from a few millimetres up to 10 cm and the thickness and shape appears to be intimately associated with deformation features. Some beds are weakly laminated suggesting an original depositional structure whilst others appear massive.

Unit 1 has been significantly deformed by folding and flexing of units, thrusting, minor normal faulting, hydro-plastic deformation and sand fluidisation. The deformation has resulted in an irregular mosaic of sediment packages, each package having its own deformational or depositional characteristic (Fig. 4). The most obvious dislocations are gravel horizons that have been displaced upwards between 90 and 110 m in the eastern face. These dislocations are also associated with extensive sediment fluidisation and water escape structures. Some sediment packages are distinct and marked by clear but frequently curved boundaries. Other packages have a more complicated form with anatomising laminae of mud enclosing sand pods. Individual packages vary in thickness from a few centimetres to about 1 m and are usually elongated, up to 5 m long. The basal surface of several packages is marked by a detachment plane beneath the very finest, ripple bedded sand. Fold axes trend NE-SW (Fig. 3a) and fold axial planes usually undulate vertically and horizontally. Shear planes undulate sub-horizontally but occasionally rise at low angles indicating thrusting from a north-westerly direction.

Table 4. Clast lithology analyses of the gravel fractions (8-16 mm, 16-32 mm) from Burgh Castle. Welsh and Northern erratics as defined in Lee *et al.* (2002).

			Carb.	Triassic				Jurassic			Cretaceous						Tertiary/Pleist.	Total Flint	Welsh	Northern	Unk.
UNIT	Sample	*n*	chert %	qzt %	v.qz %	schorl %	total %	clayst & sst	shells	*Rhaxella* chert %	mic. sst + irnst %	glauc. sst %	Greensand chert %	Chalk %	flint %	total %	chatter-marked flint %	%	Igneous + Metamorph. %	Igneous + Metamorph. + sed. %	%
8-16mm																					
5	BC950	157	0.6	0	0	0	0	1.9	3.2	0	1.9	0	0	84.2	6.3	92.4	1.3	7.6	0	0.6	0
3	BC73	788	0.6	12.2	14.1	0	26.3	0	0	0.5	0.5	0	1	0	51.8	53.3	18.4	70.2	0	0.3	0.6
3	BC71	902	0.7	10.7	7.4	0.7	18.8	0	0	0.7	1	0.1	0.8	0	62.4	64.3	14	76.4	0.1	0.7	1.9
3	BC72	752	0.7	8.4	11	0.3	19.7	0	0	2.1	0	0	0.5	0	59.1	59.6	16.2	75.3	0	0.5	1.2
2	BC900	290	0.7	11.1	15.2	0.7	27.0	0	0	0.7	0	0	0.3	0	23.9	24.2	46.0	69.9	0	0	1.4
2	BC78	587	0	7	2.4	0.2	9.6	0	0	0.9	0	0	0.2	0	60.5	60.7	24.4	84.9	0	1.7	2.9
1	BC74	719	0.8	5.1	10.8	0.3	16.2	0	0	0.6	0.1	0	0.4	0	61.9	62.4	17.2	79.1	0	1.1	1.4
16-32mm																					
3	BC73	102	0	9.8	6.9	0	16.7	0	0	0	1	1	0	0	36.3	38.3	43.1	79.4	0	0	2
3	BC71	104	0	6.7	2.9	0	9.6	0	0	0	0	0	0	0	32.7	32.7	53.8	86.5	0	2	1.9
3	BC72	49	0	6.1	4.1	0	10.2	0	0	0	0	0	0	0	40.8	40.8	49	89.8	0	0	0
2	BC900	31	3.2	6.5	3.2	3.2	12.9	0	0	0	0	0	0	0	45.2	45.2	38.7	83.9	0	0	0
2	BC78	70	0	10	4.3	0	14.3	0	0	0	0	0	0	0	25.7	25.7	54.3	80.0	0	1.4	4.3
1	BC74	66	1.5	7.6	9.1	0	16.7	0	0	1.5	0	0	0	0	42.6	42.6	37.9	80.5	0	0	0

UNIT	Sample	Coloured quartzose material %	White/colourless quartzose material %
8-16mm			
3	BC73	10.1	16.2
3	BC71	3.1	15.1
3	BC72	3.5	15.8
2	BC900	12.5	13.8
2	BC78	5.5	3.9
1	BC74	2.2	13.7

Unit 2

Unit 2 consists of coarsely interlayered non-calcareous sands with sandy diamictons varying in thickness from 60 cm to 2.5 m. The unit is thinnest in the middle of the eastern face (around 90 m Fig. 3a) and thickens to the north and south. The boundary between Unit 2 and Unit 1 is marked by an abrupt colour change. Unit 2 being much darker than Unit 1 on account of the higher water content retained in its more thinly bedded sediments. The lower boundary of Unit 2 is conformable with Unit 1 in places but erosional in others. In the southern part of the eastern face (Fig. 3a) the lower boundary is less clearly defined owing to a combination of deformation and poor exposure. The upper boundary of Unit 2 is not well exposed but is formed by an irregular erosional surface at the base of the sands and gravels of Unit 3. This surface is 15 to 50 cm above a laterally continuous diamicton within Unit 2 above which cross bedded sands of variable thickness are found.

The interlayered sands consist of moderately well sorted sands and poorly sorted sands. Individual beds are generally thin (<10 cm) and can be traced laterally for 10 cm to several metres before pinching out due to erosion, non-deposition or deformation. Upper and lower boundaries of the beds are sharp. The moderately well sorted, fine to medium grained sands (BC8 & 43, Table 2) are brownish yellow (10YR 6/6), mostly structureless but with occasional horizontal planar and rare ripple bedding. Pebbles and granules of brown and white flint and occasional white quartz and quartzite occur sporadically in isolation within the sands or as infrequent thin stringers (often one clast thick) up to 1 metre long. Very occasionally flat or deformed reworked silty clay platelets (<5 mm thick and up to 5 cm long) are present. The poorly sorted sands (BC4, Table 3) are yellowish brown (10YR 5/8), with very fine modal grain size. The sands are weakly consolidated and lack visible sedimentary structures. The heavy mineral assemblage (BC4, Table 3) is dominated by opaques (62%) and the non-opaques are dominated by epidote (46%). Amphibole, tourmaline and zircon each compose 10-12% of the non opaques whilst garnet makes up 7%.

Sandy diamicton occurs as a distinctive, laterally continuous band near the top of the unit and as an isolated lens near the base of the unit (Fig. 3a). The upper and lower boundaries of both diamictons are sharp and undulate. The lower boundary of the upper diamicton can be conformable with, or erosional across undulating beds. The upper sandy diamicton thickness varies between 10 and 25 cm: it is moderately consolidated with reddish brown (2.5YR 5/4) bands, 1-10 cm thick, and light reddish brown (2.5YR 6/4) bands,

usually < 1 cm thick. Sand content varies from 50 – 60% with a pronounced fine/very fine grained mode; clay content is 25-35% (Fig. 5). Clast content is less than 5% and dominated by flint (~80-90%) and minor quartzose (~10%) granules and pebbles. Thin laminae and lenses (<0.5 cm) of fine to medium sand can be seen towards the margins of the diamicton and very occasionally within it. In places, thin beds (~1 cm) and laminae of diamicton are festooned beneath the upper diamicton and separated by sands and rarely by lenses of gravel. The clasts within the gravel lenses (BC900, Table 4) are dominated by flint (c.70%) and quartzose material (27%) of which slightly less than half is coloured. Greensand, *Rhaxella* and Carboniferous cherts are present, each representing <1% of the sample. The heavy mineral assemblage (BC13, Table 3) contains only 36% opaques and the non opaque fraction is dominated by epidote (33%) and amphibole (26%) with zircon (14%), tourmaline (7%), and garnet (5%).

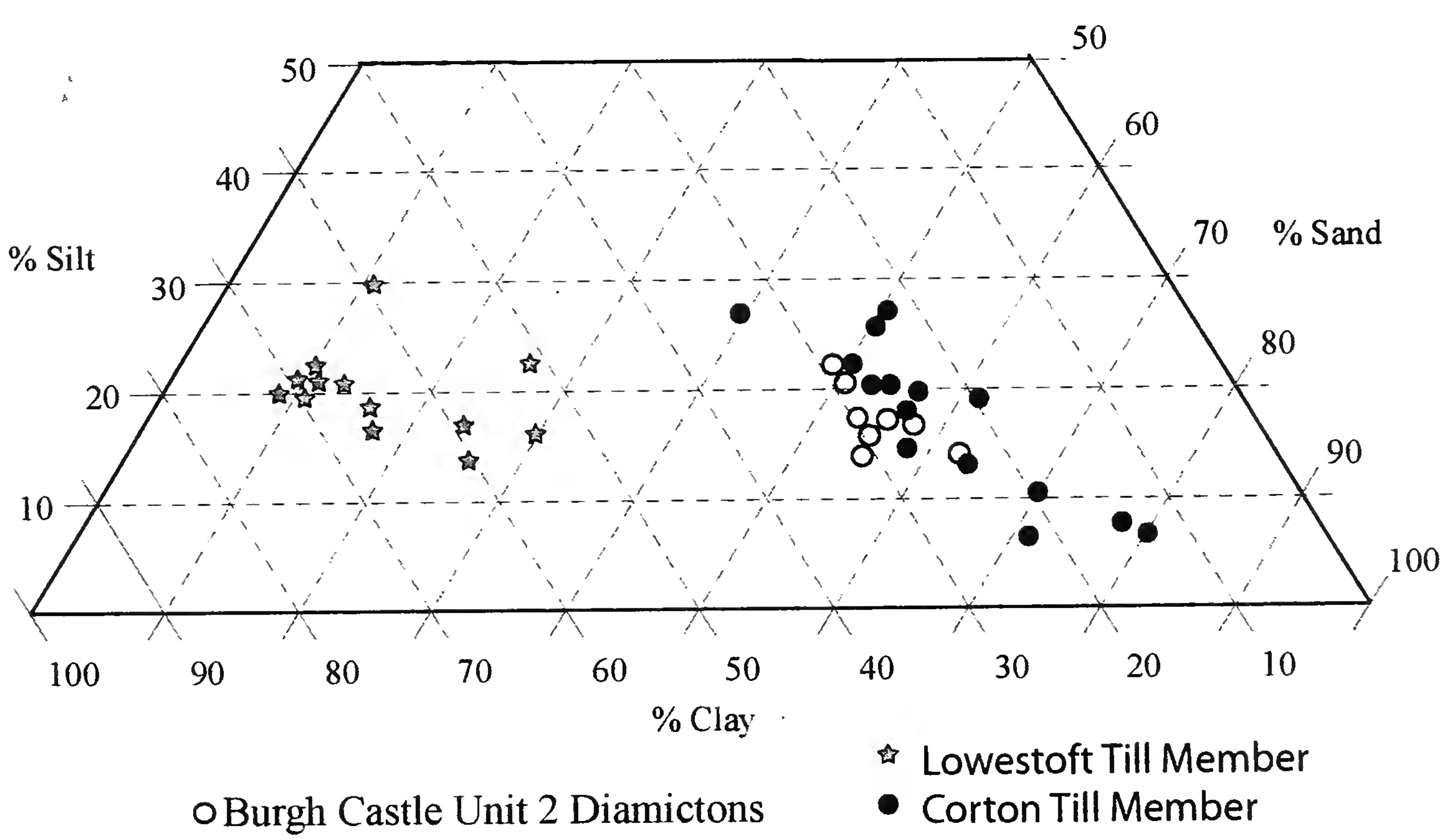

Fig. 5. Ternary plot (part) of particle size data from the diamictons at Burgh Castle and tills from northeast East Anglia (modified from Lee, 2003, Lee *at al.*, 2004).

In thin section, the upper diamicton has a heterogeneous skeleton of unsorted quartz grains with occasional discontinuous undulating laminae of sorted fine sand, and quartz and flint clasts and type III pebbles of silty, brown plasma (van der Meer, 1993). The laminae boundaries are usually sharp and a few fold noses were observed. Circular grain alignments are present and the silty brown matrix has an organised fabric in which the orientation of clay ranges from parallel to the surfaces of larger grains to a more rectangular pattern (skelsepic to lattisepic plasmic fabric of van der Meer (1993)). There are no macroscopic deformation features within the till, but it is gently arched across the section with the northern limb dipping most steeply. Clast fabric analysis reveals a strong preferred NNW – SSE orientation ($S_1 = 0.81$, $V_1 = 158°$, Fig. 3a).

The lower diamicton is very similar to the upper diamicton in texture and colour and is also non-calcareous but differs in being more massive and containing more clasts (8%) (BC 78, Table 2). The clasts have a mode in the 8 – 16 mm size range and are composed predominantly of brown flint (85%) with white and coloured quartz and quartzites (~10%) in roughly equal proportions (BC78, Table 4). *Rhaxella* and Greensand cherts are present (<1% each) but Carboniferous cherts were not recorded. Igneous and metamorphic erratics constitute almost 3%, of which 1.7% can be identified as having a northern origin (granite, granodiorite, mica schist) and the remainder cannot be provenanced. Clasts in the thickest part of the lower diamicton have a moderately strong preferred orientation with a N-S trend ($S_1 = 0.69$, $V_1 = 190°$, Figure 4a). The upper boundary of the upper diamicton has significant iron mineralization.

The upper diamicton has a planar top, which may indicate erosion and it is usually overlain by a thin unit (<8 cm) of cross bedded fine sand (foresets dip SE) followed by sands and slightly argillaceous sands similar to those at a lower level in Unit 2.

There is a marked reduction in the scale of deformation in Unit 2 compared to Unit 1 but locally the boundary between the two units is deformed in large scale folds (133-135 m in Fig. 4). On close inspection, the interlayered sands of Unit 2 show small scale, sheath folds and detached fold noses (generally with amplitudes of a few centimetres). The orientation of fold axes is predominantly NE-SW and axial planes dip at low angles in variable directions.

Unit 3

This unit is composed of undeformed, non-calcareous, cross bedded sands with and without gravel and reaches a maximum thickness of 5.5 m. Sands are moderately well sorted and vary in colour from yellowish brown (10YR 5/6) to yellow (10YR 7/6). Sands without gravel are medium to coarse grained (BC22, 23, Table 2) in the lower part of the unit and tend to be slightly finer grained in the upper part (BC19, Table 2). Sands with gravel (BC72, 71, Table 2) are weakly bimodal with moderately sorted sands (medium grain mode) and poorly sorted, sub-rounded gravels (weak mode 8-16 mm). The gravel fractions are generally matrix supported and represent a higher proportion of the sequence in the lower part of the unit. Gravel clasts are dominated by brown flints (~75%) and colourless-white quartz and quartzites (~15%) and coloured quartzose material (~3%) (BC 71, 72, Table 4). *Rhaxella*, Greensand and Carboniferous cherts are recorded with <1% each of the assemblage. Small quantities of far travelled, northern erratics (granite, granodiorite, mica schist, Old Red Sandstone) also occur (< 0.7%) and green, volcanic clasts (acidic porphyries) considered to originate from Wales were seen in one sample. The gravel at the top of Unit 3, just beneath Unit 5 at the northern end of the quarry (BC73, Tables 2, 4) is markedly coarser than other gravels and its clast content is richer in quartzose material (26%), particularly red/brown quartz and quartzite.

Heavy mineral assemblages (BC23, 19, Table 3) contain 31-42% opaques and non-opaque minerals are dominated by garnet (~29%) together with epidote (22 – 28%), amphibole (22 - 26%) and zircon (10-15%).

Depositional structures in the lower part of the unit (~1.5 m) consist of tangential and trough cross bedded sets of sands and sands with gravel. Sets range up to 80 cm in thickness and individual channels range up to 1 m in width. There are concentrations of low angle erosional planes ("reactivation surfaces") and trough cross bedding, especially in the lower part. Gravel can occur along a whole foreset, be confined to the upper region of the foreset or be concentrated in gravel lags. A ripple bedded medium sand unit 20 cm thick is present in a small outcrop near the top of the lower unit.

The lower part of the section passes up into a sequence (~ 3 m thick) of tabular sets of planar and tangentially, cross bedded, sands with and without gravels. Cross sets are generally 10 – 30 cm thick. A few, local scour surfaces (<1 m across) occur. In several beds the gravel occurs primarily or only in the upper part of the foresets. Discontinuous thin (<5

cm) gravel lags of granules and small pebbles are developed for lateral distances up to 20 m. A laterally persistent bed of moderately sorted, fine to medium cross bedded sand (25 – 40 cm thick) forms a distinctive marker in the middle of the unit. Immediately above this bed (at 153 m and approximately 7 m OD on Fig. 3a) in the eastern face and at similar levels in the northern face there are a few, truncated lenses of cross bedded sand and gravel containing abundant comminuted shell debris and very occasional larger, abraded and weathered bivalve and gastropod shell fragments (including *Arctica islandica, Macoma balthica?, Macoma obliqua, Mya arenaria, Nucella lapillus, Natica sp.*). Scarce foraminifera (*Ammonia beccarii*) which are abraded and size sorted are found within these shelly sands.

Palaeocurrent directions determined from the dips of planar and tangential cross bedding are dominantly SW with a minor component to the SE (Fig. 3a) and occasionally to the N.

Unit 4

This unit occurs only in an isolated exposure on the northern face (Fig. 3b) is composed mainly of very fine sands and laminated silts and up to 2 m thick . The unit is not present in the eastern face so must be truncated beneath the base of Unit 5 or pinched-out to the east. The absence of Unit 4 in the eastern face, the elevation of the base of Unit 4 in the northern face and the low angle of dip in Unit 3 in the northern face suggest that the base of the Unit 4 is discordant and may cut down several metres into Unit 3 (Fig. 3b).

Sands are predominantly very fine grained (BC 304, 307, Table 2) and ripple bedded: their colour ranges from pale yellow (2.5YR 8/4) to light yellowish brown (2.5YR 6/4). Clayey silts (BC 308, Table 2) are light yellowish brown (2.5YR 6/4) and laminated. The entire unit is very calcareous ($CaCO_3$ content ranges from 8% in fine grained sands to 40% in the silts) apparently derived as distinct grains of chalk. Bed thicknesses vary from 10 to 40 cm and the lower boundaries are either scalloped or underlying structures are partially truncated. Ripple bedding within the sands indicates a SE current flow. Rippled sand beds occasionally fine upwards. The upper 60 cm of the unit is composed of predominantly laminated fine sand (BC310, Table 2) with occasional thin laminae of medium to coarse sand and chalk granules. The upper part of the unit has been deformed and folded around a

downward, sub-horizontal lens of diamicton from Unit 5. The axial plane of the fold dips 10°, with a bearing of 310°. The sands immediately underlying Unit 5 are heavily indurated locally with a calcareous cement. The cemented intervals are up to 8 cm thick and extend laterally up to 2 m.

The heavy mineral assemblage (BC 308, Table 3) is marked by high proportion of opaques (66%). Epidote (36%) and amphibole (30%) dominate the non-opaque fraction with apatite (10%) and garnet (7%) and zircon (6%) being the other main components.

Unit 5

This unit, like Unit 4, only outcrops along the northern edge of the quarry. It is thickest (~6 m) and best exposed in a 'channel-like' feature in the northern face (Fig. 3b) which is the southern end of a small outlier mapped to the north and west. The lower boundary of this unit is generally obscured by talus on the northern face and its upper boundary is disturbed by quarrying. Unit 5 is composed of a black (7.5YR 2/5) to brown (7.5YR 5/2), calcareous, clay-rich, matrix supported diamicton containing abundant chalk (84.2%) clasts together with flint (7.6%), Jurassic shell fragments and sandstone clasts (5.1%) together with traces of Cretaceous sandstone and Carboniferous chert clasts (Table 4). The matrix (<2 mm) is composed of 48% clay, 27% silt and 25% sand (Table 2). Clasts >2 mm constitute 13% of the total mass of the unit. Clast fabric analysis reveals a moderate strength ($S_1 = 0.55$, $V_1 = 018°$) and the principal eigenvector has a NNE – SSW trend, roughly parallel with the orientation of striations on chalk clasts (Fig. 3b).

CORRELATION AND PALAEOENVIRONMENTAL INTERPRETATION

The correlation of the units recognised in this paper with those identified by Bridge & Hopson (1988) in the same pit is shown in Table 5. Hopson and Bridge (1987) correlate the sand and gravel outwash with the Leet Hill Sand and Gravel Member. Bridge and Hopson (1988) recorded ice wedge casts beneath each of their till bands although none were observed in thus study.

The lithological, sedimentological and structural properties of these sediments can be fitted into the recently-established lithostratigraphic frameworks proposed for the glacial (Lee *et al.*, 2004a, b) and pre-glacial sediments (Rose *et al.*, 2001) of the area (Table 1). All the sands at Burgh Castle have non-opaque, heavy mineral suites with high concentrations of

Table 5: Correlation of Units identified by Bridge & Hopson (1988) with those recognised in this paper.

Bridge & Hopson, 1988	This Paper	
Lowestoft Till	Unit 5	Lowestoft Till Mb
Corton Sands	Unit 4	"Corton sand facies"
Unit 2 Unit 3 Unit 4	Unit 3	Leet Hill Sand & Gravel Mb + Corton Till Mb.
Unit 5 with interbedded diamictons of N Sea Drift derivation	Unit 2 Unit 1	

less stable minerals (particularly amphibole and epidote) which indicate a persistent and significant glacial input to the depositional system (Perrin *et al.*,1979; Lee *et al.*, 2002, 2004a, b). A summary of the stratigraphic correlation, sedimentary facies and palaeoenvironmental interpretation of the section at Burgh Castle (discussed below) is presented graphically in Table 6.

Units 1, 2 and 3

The sediments of Unit 1 were laid down under variable flow regimes. The upward coarsening sets of fine to medium, ripple bedded sand suggest repeated progradations with a fluctuating sediment supply. It is not clear whether or not these sediments were deposited from shallow unchannelised or channelised flows but the absence of climbing ripples indicates current reworking of sediments was more significant than deposition from suspension (Jopling & Walker, 1968). The medium grained, cross bedded sands were probably deposited as sand waves or bars with occasional quiescence of the water reflected by settling of silty clay to form drapes on some foresets. The thin beds of mud were probably also deposited in stagnant water, perhaps in ephemeral ponds. The cross bedded gravels seen near the base of Unit 1 may have been deposited as bars within local channels.

The bedding within the interlayered sands of Unit 2 is generally thinner and more discontinuous than that in Unit 1 and reflects a different depositional regime. The absence of upward fining sequences, the thin beds and the sharp boundaries between beds suggests

Table 6. Summary of sedimentary facies, palaeoenvironmental interpretation and stratigraphic correlation of the section in Welcome Pit, Burgh Castle. Stratigraphic units as defined by Lee *et al.* (2004b).

UNIT	STRATIGRAPHIC CORRELATION	SEDIMENTS	DEPOSITIONAL ENVIRONMENT	MOVEMENT OF ICE MARGIN (N – S)	Possible MIS
5	Lowestoft Till Mb.	Chalky, clay rich diamicton	Subglacial	⇒	12
4	"Corton sand facies"	Ripple bedded sands & silts	Distal outwash	⇒ or ⇐	12
3	Leet Hill Sand & Gravel Mb.	Cross bedded sands and gravels	Proximal braided outwash plain	⇐	16
2	Corton Till Mb.	Thin bedded fine to medium sands interbedded with diamictons (deformed)	Ice marginal outwash fan intermittently overidden by ice sheet	→ →	
1		Ripple and cross bedded fine to medium sands (deformed)	Ice marginal outwash fan	⇒	

that deposition was largely episodic. The poorly sorted sands with occasional stringers of fine gravel were probably deposited from relatively dense intermediate flows and the cleaner sands resulted from current sorting (Zieliński & van Loon, 1996). Poorly sorted sands ("diamictic sands") described by Zieliński & van Loon (1996) from Poland, are thought to have been deposited from flows extending up to 900 m from the glacier's foot (Kasprzak & Kozarski 1989). The bedding at Burgh Castle is notably thinner than that in the Polish example and probably reflects both smaller scale and more local flows.

The reddish brown colour and texture of the Unit 2 diamictons (Fig. 5) enable comparison and likely correlation with the Corton Till Member of the Happisburgh Formation (Lee *et al.,* 2004b). As in the Corton Till Member, the diamictons contains a significant, albeit small, component of far travelled igneous and metamorphic clasts that can be traced to northern UK sources (Lee *et al.*, 2002). The ratios of flint to quartz and coloured to colourless quartzose clasts (Fig. 6) suggests that much of the Corton Till was derived locally by glacial scouring of the marine Wroxham Crag Formation which would have been widely exposed at the surface as the ice sheet moved south across Norfolk. Several factors suggest that the diamictons in Unit 2 were deposited subglacially as a till: the clast fabrics are moderate to strong with a consistent north-south orientation; the beds are overconsolidated; upper and lower bed boundaries are sharp and, rotation structures are present in thin section (van der Meer, 1993). Whilst the banding and local thin beds and laminae of sand within the till might be taken to indicate waterlain till, individual consolidated till bands can be traced over several metres and do not loose their character as they thin and eventually terminate. There are no structural deformation features within the tills to indicate slumping or mass movement. The lack of any grading within the tills or the surrounding sands and the absence of dropstones suggests that the sand beds and laminae may have been deposited subglacially. The extensive deformation within the sands of Units 1 and 2 is interpreted as the result of the stress and hydrodynamic regime imposed on the sediments by the movement of ice across the area during and after the deposition of the diamictons of Unit 2.

The sediments of Units 1 and 2 are interpreted as having been deposited on a sandy glaciofluvial outwash plain across which the ice margin repeatedly advanced and retreated depositing thin subglacial till. The intervening, finer grained sands probably indicate low meltwater discharge and that predominantly fine sediment was available at the front of the

ice margin. Deposition of fine sands in an ice marginal position is more likely when an ice sheet is stable or advancing (Krüger, 1997). The Corton Till at Corton, 8 km to the southeast, has also been interpreted as forming in an ice marginal environment (Lee, 2001).

The sediments of Unit 3 have a coarser grain size, more abundant gravel and larger bedforms than the lower units and reflect a change to a higher energy depositional environment. Deposition was primarily from bedload and the character of the cross bedding suggests an aggrading sequence of migrating low to medium scale sand waves through which shallow channels were only locally developed, mainly in the lower part of the unit. Gravel stringers were probably deposited as lags during periods of high flow. The local accumulations of broken and abraded marine shells are interpreted as reflecting reworking of older Crag deposits by the glacial system. The decrease in grain size and set thickness upwards in Unit 3 suggests declining energy in the system until, near the top, this pattern changed and coarse gravel was deposited under a very high flow regime. The higher energy system responsible for deposition of these sediments, the lack of deformation and the absence of tills, suggests that they accumulated on a braided, glaciofluvial outwash plain in front of a retreating ice sheet. Palaeocurrents suggest drainage was predominantly to the southwest.

The flint:quartz ratios and coloured: colourless quartz ratio of the gravels from Units 1, 2 and 3 (Fig. 6) allows a correlation with the Leet Hill Sand and Gravel Member (LHSG) from Leet Hill (Rose *et al.,* 1999a). This correlation is strengthened by the persistent presence of a distinct northern erratic component and Carboniferous chert (Rose *et al.* 1999a, 2000b, 2002, Hopson & Bridge, 1987). The heavy mineral assemblages within the sands of Units 1, 2 and 3 (Fig. 7) contain significant quantities of less stable minerals and are similar to lithofacies B and C from the LHSG (Lee *et al.*, 2004a). However, the heavy mineral assemblages of Unit 3 contain a higher concentration of garnet and zircon than the underlying units, the reverse of the trend seen at Leet Hill. Lee *et al.* (2004b) state that the LHSG is characterised by having higher apatite content (7% ±2.8) relative to other non-diamicton units. Whilst apatite is present in Units 1-3 it is generally at much lower percentages (1.5-5.4%). This discrepancy is probably not critical to the correlation, particularly as apatite may be locally derived from the underlying Crag sediments.

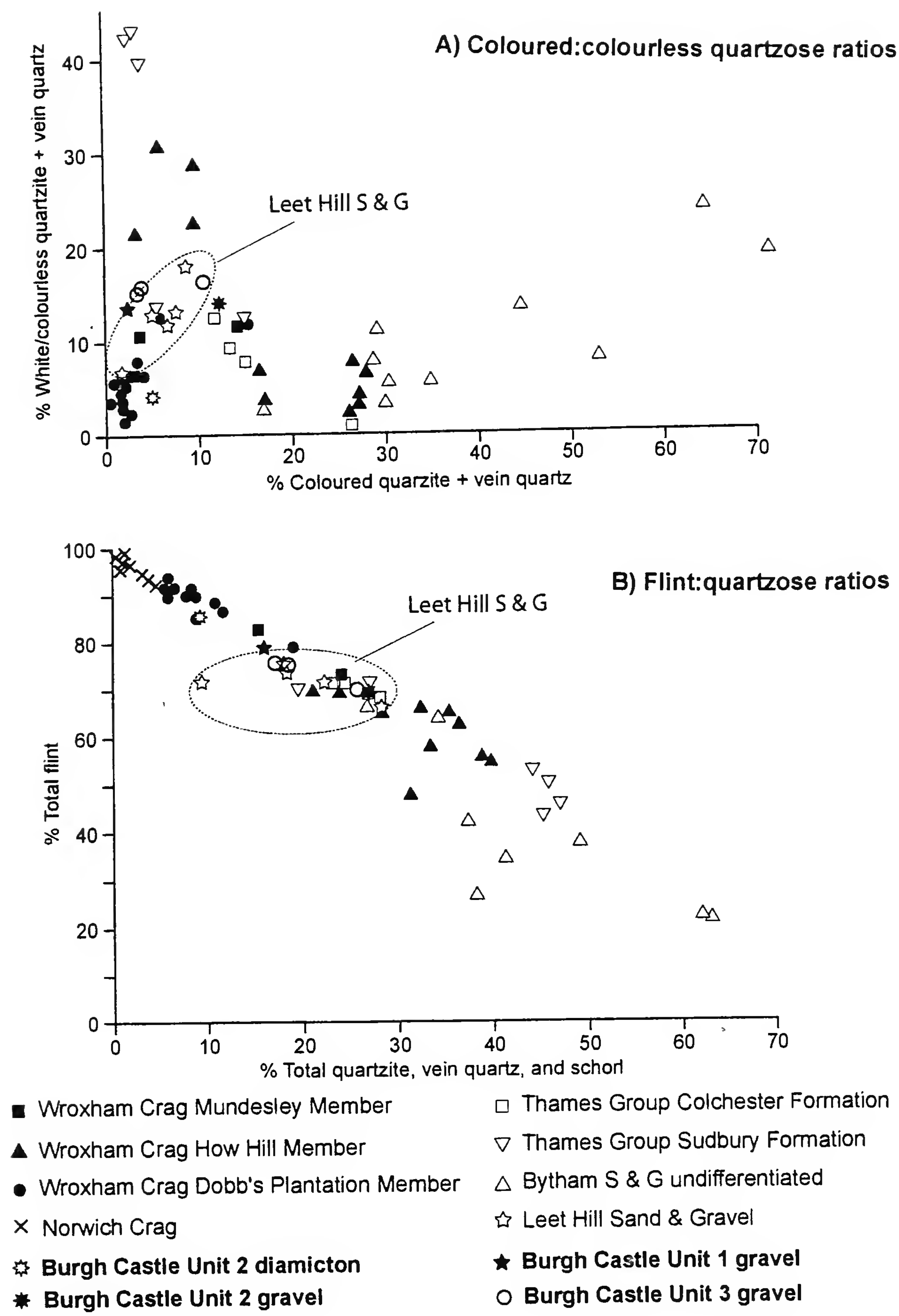

Fig. 6. Comparison of clast lithology analyses of gravel fractions (8-16 mm) from Burgh Castle with those for lithostratigraphic units in Rose *et al.* (1999a, 2001), Lee *et al.* (2002, 2004b). Plots A and B modified from Rose *et al.* (2001).

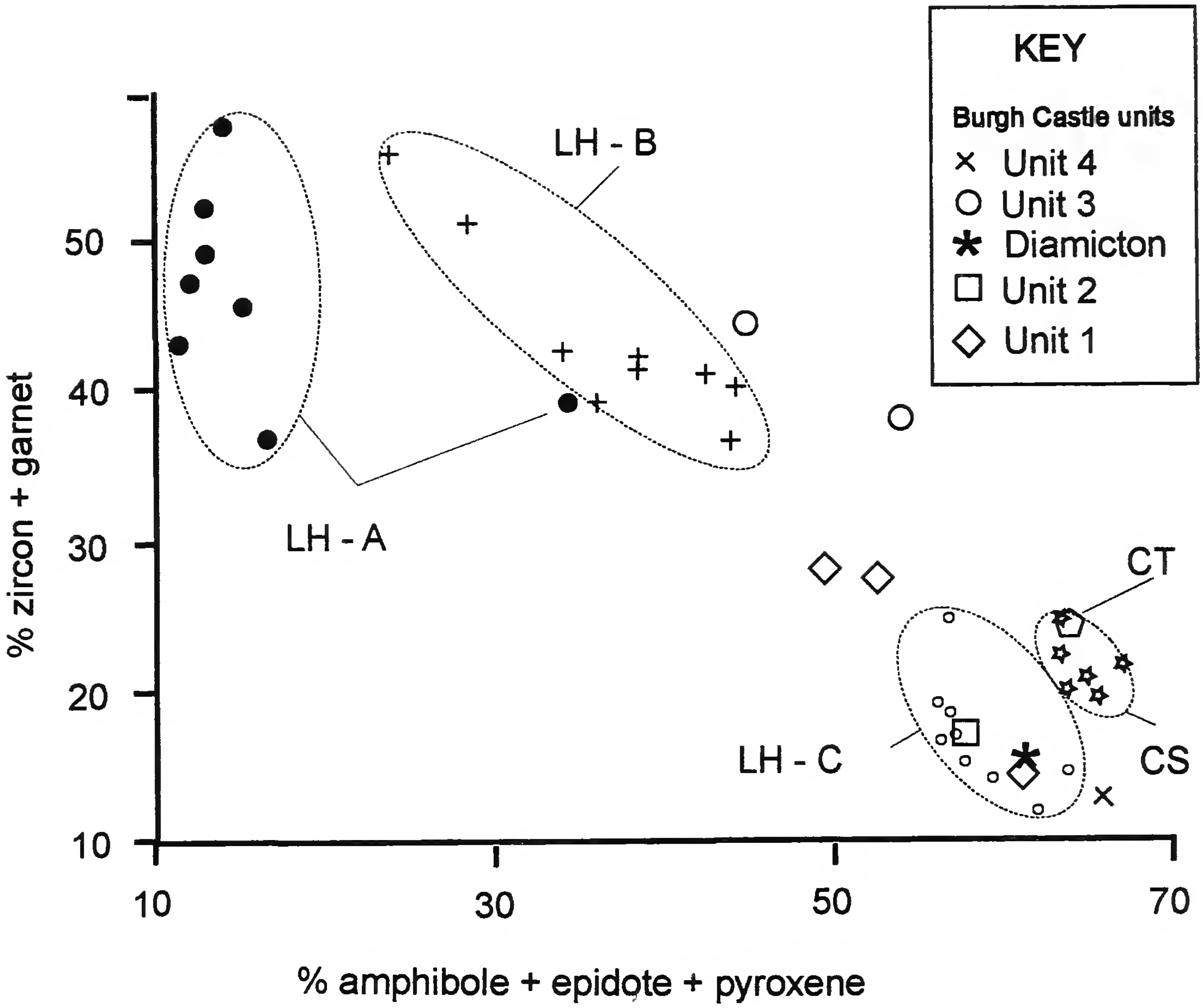

Fig. 7. Comparison of heavy mineral assemblages contained in sands and gravels at Burgh Castle with sands and gravels at Leet Hill (LH) lithofacies A, B and C, Corton Sand (CS) Lee (2003), Lee *et al.* (2004) and the average for the Corton Till (CT) in East Anglia Lee *et al.* (2004).

The low gravel content and thin bedded facies of Units 1 and 2 are very poorly represented in the LHSG at Leet Hill where the facies is more similar to that of Unit 3 with extensive gravel, large scale cross bedding and well developed channeling. Extensive borehole sampling by Hopson and Bridge (1987) showed that where the LHSG were thickest in the Raveningham - Lound depression, running ENE – WSW to the south of Burgh Castle (Fig.1), the sediments they encountered contained considerably less gravel than in the area to

the south and west which suggests the development of a local more sand rich subfacies within the LHSG in the area around Lound and Burgh Castle.

Unit 4

Sediments of Unit 4 have only a small outcrop but reflect a marked change to a lower energy depositional environment than the units below. The thinly bedded, rippled, very fine sands were probably deposited by shallow streams on a distal, glaciofluvial outwash plain whilst the laminated silts formed in shallow ephemeral pools of standing water on the surface of the plain. The pale yellow, chalk-rich sands of Unit 4 are similar to the facies described by Lee *et al.* (2004b) as the Corton Sand Member and both occupy a stratigraphic position immediately below the Lowestoft Till Member (Unit 5, see below). However, the heavy mineral assemblage is different from that described for the Corton Sand Member (Lee *et al.*, 2004b) in that the percentages of opaque minerals and apatite species are higher, and epidote and garnet are significantly lower, and suggesting closer affinity with the Lowestoft Formation described by Lee *et al.* (2004b). Bridge and Hopson (1988) recorded Corton Sands up to 2.5 m thick in the northern part of the pit in an area to the west of the present day exposures. Unit 4 is thus broadly identified as being of "Corton sand facies" but not necessarily correlative with the Corton Sand Member of Lee *et al.* (2004b).

The high chalk content of these Unit 4 sediments is in marked contrast to the sediments below and reflects a fundamental change in the sediment supply to the depositional system (see below).

Unit 5

The clast fabric and clast striations of the uppermost black to brown, massive, clay rich matrix supported diamicton suggest it was deposited as a till by ice moving southwards. The clay-rich facies with abundant Chalk and occasional Jurassic fossil clasts of Unit 5 is very similar to and therefore correlated with the Lowestoft Till Member at Corton (Lee *et al.* 2004b; see also Fig. 5).

DISCUSSION

Evidence for multiple glaciations

Historically, two coeval ice sheets were thought to have deposited sediments of the Lowestoft Till Member (British glacier) and North Sea Drift, including those of the Corton Till Member, (Scandinavian glacier) (Perrin *et al.,* 1979; Bowen *et al.*, 1986). These ice sheets have generally been considered to be of Anglian/Elsterian age and correlated with the Marine Oxygen Isotope Stage (MIS) 12 (Rose, 1989a; Bowen, 1999). Lee *et al.* (2002) have argued that there is no convincing evidence that the ice sheet depositing the Corton Till Member originated in Scandinavia and that provenancing of erratic clast lithologies and palynomorphs demonstrate that the ice is of British origin. Clast lithological analysis undertaken as part of this study supports this view; clast lithologies suggest a British source with a predominantly local content.

The distinct differences in both texture and composition of the Corton and Lowestoft tills at Burgh Castle demonstrate, as other regional studies have done, that they were deposited by ice sheets with significantly different flow configurations (Perrin et al., 1979; Lee, 2003; Lee *et al.*, 2004b). These tills are separated within the sequence at Burgh Castle by two glaciofluvial units. The lower glaciofluvial unit is the Leet Hill Sand and Gravel Member of the Happisburgh Formation and this can be genetically tied to the Corton Till Member. The absence of chalk is considered a primary feature rather than a result of decalcification because of the presence of comminuted, calcareous shelly material in Unit 3. The overlying chalk-rich sands, (Unit 4, "Corton sand facies") show affinities to the Lowestoft Till and are separated from underlying Leet Hill Sands and Gravels by a marked disconformity (between Units 3 and 4 on Fig. 3b).

The sedimentary record at Burgh Castle indicates a significant ice retreat or deglaciation could have occurred between deposition of the Corton and Lowestoft Till members but there is no evidence for the duration of the hiatus or surface processes that occurred during it. However, the interbedding of subglacially deposited Corton Till Member sediments with the Leet Hill Sand and Gravel Member sediments at Burgh Castle also substantiates the observations of Lee *et al.* (2004a) that the third youngest Bytham River terrace deposits containing till clasts at Leet Hill (Timworth Member) were coeval with the formation of the Corton Till Member. Based on an analysis of the evidence of till clasts, erratics and heavy minerals from these Bytham River terrace deposits and using the concept

of terrace aggradation in 100 ka modulated cold stages, Lee *et al.* (2004a) argued that the deposits of the Happisburgh Formation (including the Corton Till Member) were deposited during a pre-Anglian, Middle Pleistocene glaciation which is attributed to MIS 16.

The sedimentological record and correlation of the section at Burgh Castle is consistent with the argument for an earlier pre-Anglian glaciation and this correlation is shown on Table 5.

Evidence for glaciations during the Cromerian Complex

Interpretation of the Corton Till as being of MIS 16 age (Lee *et al.* 2004a) would place these sediments in the Cromerian Complex and separate them in time from the Lowestoft Till by two temperate MIS. No clear evidence for interglacial or temperate stage sediments (marine or terrestrial) has been found at Burgh Castle between the Corton and Lowestoft Tills. The possibility that the marine shells and foraminifera in Unit 3 are contemporaneous is not considered likely as the sediment was deposited by glaciofluvial processes and the shells and microfossils were probably reworked from the underlying Crag. However, the possibility cannot be completely excluded. Similar shelly material has been found in sands lying between the Corton and Lowestoft Tills nearby, e.g. at Corton (Blake, 1878, 1890, P. E .Long, pers. com.) and Billockby (Fig. 1; Woodward, 1881). There has been an ongoing debate since Victorian times as to whether the shells are contemporaneous or glacially reworked, older Crag fossils. Wood and Harmer (in Wood, 1874, Volume 3, p. xxii – xxiii) reviewed this issue and offered several reasons why they felt the shells were "contemporaneous and not derivative". Their conclusion hinged largely on the preservation of very delicate shells (not seen at Burgh Castle) which they considered unlikely to have survived reworking. The debate on these shells has been most recently revisited by Cambridge (1972) but not resolved. Lee *et al.* (2006) meanwhile, have described sedimentary structures and heavy mineral assemblages from "Corton sand facies" at Pakefield, and have interpreted them as a shallow marine facies (Pakefield Member) of the Wroxham Crag Formation.

Evidence for neotectonic processes during the Middle Pleistocene

Regional neotectonic uplift of inland regions of southern and south east England during the Pleistocene has been demonstrated by, e.g., Maddy, (1997), Maddy *et al.* (2000, 2001) and Westaway *et al.* (2002) and is an essential component in the formation of the Pleistocene terraces of the Thames and Bytham rivers. Evidence for more subtle and local neotectonic uplift affecting drainage patterns of northern East Anglia during post early Middle Pleistocene times was explored by Rose *et al.* (2002) and showed a complex history but with minimal timing control. The palaeocurrent directions in the upper part of the Leet Hill Sands and Gravels at both Burgh Castle (Unit 3) and Leet Hill (Rose *et al.*, 1999a) are southerly, with a bias towards the southwest at Burgh Castle. A southerly and particularly a southwesterly flow is surprising as the palaeoslope both before the Happisburgh Glaciation and after the Anglian Glaciation was generally eastwards towards the North Sea Basin (Rose *et al.* 1999b). This might suggest the existence of a barrier to the east, although there is no supporting evidence. Ice is unlikely to have formed an eastern barrier as the clast fabrics in the Corton Till at Burgh Castle suggest ice moved across the area in a south to southeasterly direction and the southern limit of the Corton Till (and its equivalent Starston Till) can be traced southwestwards into west Suffolk (Figure 1). Burgh Castle, Leet Hill and the deep Crag basin known as the Stradbroke Trough (Figure 1) lie on a northeast – southwest trend and the parallelism with the palaeocurrents may indicate a subtle structural influence on the outwash drainage pattern.

Conclusions

1. The sequence at Burgh Castle, southeast Norfolk, is composed of interbedded Corton Till Member and Leet Hill Sand and Gravel Member of the Happsiburgh Formation, overlain locally by possible outwash sands and till of the Lowestoft Formation. The two formations are separated by a disconformity.
2. The Leet Hill Sands and Gravels were deposited as glaciofluvial outwash close to the margin of a British ice sheet which periodically advanced and retreated across the outwash depositing thin subglacial tills.

3. The inclusion of till within the Leet Hill Sands and Gravels (Unit 2) is taken as evidence that they are the lateral equivalent the Timworth Terrace Member of the Bytham Sands and Gravels as recognised as Leet Hill.
4. The Leet Hill Sand and Gravel Member and the tills (Units 1, 2 & 3) are correlated, on the basis of lithology, texture and ice flow direction, with the Happisburgh Glaciation which has been suggested to occur in MIS16.
5. Following a major retreat of the ice a younger, British ice sheet advanced and deposited the outwash sands ("Corton sand facies") and the Lowestoft Till attributed to the Anglian/Elsterian Glaciation of MIS12 age.
6. The fine chalky sands which lie below the Lowestoft Till and have historically been attributed to the Corton Sands (*sensu lato*) may not all be of the same age.
7. The interpretation of the section at Burgh Castle is consistent with earlier proposals for both multiple Middle Pleistocene glaciations and an earlier pre-Anglian glaciation (Happisburgh Glaciation)
8. Glaciofluvial drainage associated with the Happisburgh Glaciation may have been structurally influenced along a controlling northeast southwest trough visible in the underlying Crag.

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DISCUSSION

THE STRATIGRAPHY OF THE BRITON'S LANE BOREHOLE AND QUARRY, BEESTON REGIS, NORTH-EAST NORFOLK – DISCUSSION

Banham, P.H.

Department of Geology, Royal Holloway, University of London
Email: peter.h.banham@ntlworld.com

The recent Bulletin paper by Pawley et al. (2005) is particularly welcome because detailed observations of the glacifluvial sands and gravels within Briton's Lane quarry are for the first time extended by borehole to connect with the tills below. Furthermore, the wider stratigraphical interpretation is acceptably restrained, following publication of the work of Hoare & Connell (2004) in an earlier paper in the Bulletin.

Concerning the Briton's Lane Sands and Gravels (BLS&Gs) specifically, in terms of process, Pawley *et al.* conclude that they "represent a thick drape of outwash deposited following the construction of the Cromer Ridge". This conclusion is broadly consistent with the results of most earlier work, including that of C.E. Ranson recently reported in the Bulletin (in Banham, 2000), but strangely not acknowledged by Pawley *et al.* This is quite surprising, for although Ranson carried out no pollen or heavy mineral analyses, he did examine nearly 900 clasts (8-32 mm intermediate dimension) from two stations within the BLS&Gs at this the type site. His results appear to be in touch with those of Pawley *et al*, given that they examined a different size fraction (4-8 mm). Moreover, Ranson provided an analysis of nearly 13,000 clasts from 36 other sites in north-east Norfolk, which then (c. 1965 -1985) exposed sands and gravels which he considered to be laterally equivalent to the BLS&Gs.

From this analysis, from general facies observations and from good flow indicators at eight sites, Ranson (in Banham, 2000) thought these deposits represented outwash from an ice sheet (Anglian, probably largely Lowestoft) lying broadly to the north-west. In so doing he was careful to acknowledge the value of earlier insights into the nature of that ice margin, particularly those of Rose (in Banham *et al.*, 1975) and of Funnell (1976).

THE STRATIGRAPHY OF THE BRITON'S LANE BOREHOLE AND QUARRY, BEESTON REGIS, NORTH-EAST NORFOLK– REPLY

Steven M. Pawley[1*] Jonathan R. Lee[2], James B. Riding[2], Brian S.P. Moorlock[2,1], Richard J.O. Hamblin[2,1], James Rose[1], & Richard G. Crofts[2]

[1]Department of Geography, Royal Holloway, University of London, Egham, Surrey. TW20 0EX

[2]British Geological Survey, Keyworth, Nottingham. NG12 5GG

*email: S.M.Pawley@rhul.ac.uk

We were interested to read the comments by Banham on our paper published in Bulletin 54. We appreciate the comments that have been made and we apologise for not acknowledging C.E. Ranson's work in our paper. The data published in Banham (2000) is particularly important as it quantitatively determines the clast content and palaeoflow directions of the Briton's Lane Sands and Gravels over the entire region of the Cromer Ridge and lateral equivalents in north-west Norfolk.

However it is nice to see that the findings of our paper are broadly consistent with the conclusions of earlier workers in terms of the depositional processes forming the Briton's Lane Sand and Gravel. We are also pleased that our clast lithological data is compatible with the interpretation of Banham (2000), proposing that the outwash at Briton's Lane was deposited from southward flowing ice moving off the North Sea Basin, whereas north-west Norfolk may have received a larger contribution from ice melting back towards the west or northwest.

The lithostratigraphy at Briton's Lane quarry supports the revised glacial stratigraphy for eastern England (Lee *et al.*, 2004; Hamblin *et al.*, 2005), finding that the tills and glaciolacustrine sediments underlying the Briton's Lane Sand and Gravel were deposited from British rather than Scandinavian-sourced ice sheets. However, we are still not sure about the timing of these ice advances and whether the Briton's Lane Formation was deposited during the Anglian Glaciation or during MIS 6 as proposed in Hamblin *et al.* (2000, 2005). This issue is the subject of ongoing research in the geochronology laboratories at the Department of Geography at Royal Holloway University of London.

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The figure on the front cover is figure 9 from the paper by Poulton *et al.* in this issue of the Bulletin, illustrating the seasonal erosional processes that occur at Happisburgh cliffs on the Norfolk coast.

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